Evaluation of Daylight Quality, Visual Comfort, and Energy Performance in Nordic Museums: A Case Study of Malmö Konsthall

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Abstract

This thesis investigates daylight performance and energy use in museum environments using Malmö Konsthall as a case study. The aim is to evaluate daylight quality, visual comfort, artwork protection, and energy performance, and to explore how these aspects can be balanced through design strategies. The study combines field measurements, climate-based daylight simulations, energy simulations, and a visitor survey. Daylight performance was assessed using Daylight Factor (DF), Useful Daylight Illuminance (UDI), Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE), Daylight Glare Probability (DGP), and annual average illuminance on artworks. Energy simulations were conducted to evaluate heating demand and the influence of building envelope and lighting conditions.

The results show that the existing daylight conditions provide high daylight availability but result in excessive illuminance on several artworks. To address this issue, daylight improvement strategies, including partial skylight blocking and façade glazing modifications, were investigated. These measures reduced artwork illuminance levels and improved visual comfort while maintaining sufficient daylight within the exhibition space. The visitor survey indicated that the lighting environment was generally perceived as comfortable and visually pleasant, complementing the simulation-based analysis. From an energy perspective, building envelope improvements reduced heating demand by 16%, demonstrating the importance of integrating daylight and energy considerations in museum design.

Overall, the study demonstrates that achieving a balance between daylight quality, artwork protection, visual comfort, and energy efficiency requires an integrated design approach. Although the study focuses on Malmö Konsthall, the findings provide broader insights into the challenges of balancing daylight availability, artwork conservation, and energy performance in Nordic museum environments.

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Glossary

DF – Daylight Factor: The ratio between indoor and outdoor illuminance under overcast sky conditions, expressed as a percentage.

DGP – Daylight Glare Probability: A metric used to assess the probability of visual discomfort caused by daylight glare.

sDA – Spatial Daylight Autonomy: The percentage of floor area that receives a minimum illuminance level (commonly 300 lux) for a defined percentage of occupied hours.

UDI – Useful Daylight Illuminance: The percentage of time when daylight illuminance levels fall within a useful range, typically between 100 and 3000 lux.

ASE – Annual Sunlight Exposure: The percentage of floor area receiving more than 1000 lux of direct sunlight for more than 250 hours per year.

WWR – Window-to-Wall Ratio: The percentage of a façade area that is occupied by windows.

VLT – Visible Light Transmittance: The fraction of visible light transmitted through a glazing system.

Rhino – Rhinoceros 3D: A 3D modelling software used for creating the geometric model of the building.

GH – Grasshopper: A visual programming tool used together with Rhino for parametric modelling.

1. Introduction

Light plays a fundamental role in human vision, health, and overall well-being. It is an environmental factor that influences biological processes in the body, especially circadian rhythms, which control sleep, hormones, and how alert we feel during the day (Wirz-Justice et al., 2021). Exposure to natural daylight is especially important, as humans are biologically adapted to its dynamic intensity and spectral composition. Daylight provides high illumination levels and a broad spectrum rich in short wavelengths, which are essential for maintaining circadian entrainment and supporting physiological and psychological health (Integrated Systems Europe, 2025). If people do not receive sufficient exposure to appropriate lighting conditions, especially during daytime, these processes can be disturbed, leading to fatigue, poor sleep quality, reduced concentration, and lower well-being. Therefore, access to daylight and well-designed lighting environments is essential not only for visual performance but also for creating healthy indoor environments (Knoop et al., 2020).

In museums, light is not only used to make objects visible. It also affects how visitors experience the exhibition space. The way light is distributed in the gallery can draw attention to certain artworks and create a specific atmosphere. Museum lighting thus becomes an important part of the exhibition design, not only a technical element (LedaPlus, n.d.). In addition, daylight utilization contributes to reduce the reliance on electric lighting while offering the potential for improving visual conditions. However, it must be carefully controlled to avoid glare, uneven distribution, and potential damage to light-sensitive artworks (Iordanidou, 2017).

In the Nordic context, daylight conditions are more challenging due to strong seasonal variations and specific climate characteristics. During winter, daylight is limited to only a few hours per day, and dark overcast skies are dominant (Dubois et al., 2025). In addition, low sun angles create long shadows, which make outdoor spaces darker and reduce daylight availability inside buildings (IAAC, 2022).

Previous studies have shown that daylight performance in museums depends on several factors, such as the design of openings, glare control, and light distribution. Research has also shown that daylight openings can improve the connection to the outside environment, but poor control may lead to high contrasts and discomfort (Iordanidou, 2017). In addition, studies indicate that user perception of light may differ from simulation results, since electric lighting and outdoor conditions can influence how spaces are experienced (Madhoon, 2019). Other research highlights the importance of maintenance, as in Faaborg Museum in Denmark, where insufficient cleaning of skylights led to dim lighting conditions (Niels, 1984). Research also shows that uncontrolled daylight can cause glare, uneven light distribution, and potential damage to artworks, especially in historical buildings where daylight is difficult to manage (van der Zaag, 2017).

Studies indicate that passive solutions such as skylights alone are not enough to protect artworks, and additional control strategies are needed (Marcin, 2026). Excessive daylight can also affect indoor conditions like temperature and humidity, which may negatively impact collections (Xilian, 2020).

Daylighting guidance shows that good daylight performance depends on controlling light distribution and limiting excessive contrasts that can cause visual adaptation problems. This can be influenced by the geometry of openings (e.g., placement and shaping of openings) and by interior surface reflectance, these effects are often investigated using daylight simulations (Dubois et al., 2025).

The thesis is organised as follows. The first chapter introduces the background and context. The second chapter presents the literature review. The third chapter describes the methodology and simulation approach. The fourth chapter presents the results, followed by a parametric study in the fifth chapter. The sixth chapter discusses the findings, while the seventh chapter presents the conclusions. The final chapters address the limitations of the study and suggest directions for future research.

1.1 Daylighting Challenges and Energy Considerations in Museums

Previous studies show that architectural design parameters, such as window size, orientation, and surface reflectance, have a strong influence on daylight distribution and visual comfort (Eugenia & Tumpa, 2019). In museum environments, daylight is often studied in relation to visual quality and the preservation of artworks, while its impact on energy use has received less attention. Some studies indicate that daylight can reduce the need for electric lighting, but it may also increase cooling demand if not properly controlled (Ma et al., 2023). However, the relationship between daylight performance and energy use in museum spaces, particularly in Nordic contexts, remains insufficiently explored.

Museum lighting guidelines show that light in exhibitions must be carefully balanced. On one hand, light helps visitors see artworks clearly and understand colours and details. On the other hand, too much light can slowly damage sensitive materials such as textiles and paper. Therefore, lower light levels are often recommended for fragile objects (Museums Galleries Scotland, 2024).

Swedish daylight guidelines highlight that daylight is important for human well-being, as access to natural light can support circadian rhythms and improve visual comfort (Arbetsmiljöverket, 2019). While museum visitors are typically exposed to the space for a limited period of time, museum staff experience these conditions for much longer durations. Therefore, daylight design in museums should consider not only the conservation of artworks and visitor experience, but also the health and well-being of staff working in the environment.

This creates a fundamental conflict in museum design: the need to limit light exposure for conservation purposes while simultaneously providing adequate lighting conditions for visitors and staff. This leads to a key challenge in museum daylight design: how to achieve a balance between protecting artworks and ensuring a comfortable and visually effective environment for people.

1.2 Motivation

The motivation for this thesis stems from the need to better understand how daylight can be used effectively in museum environments while balancing visual comfort, artwork protection, and energy performance. In large exhibition spaces, daylight can enhance the visitor experience and reduce the need for electric lighting, but it may also introduce challenges such as excessive illuminance on sensitive artworks and increased energy demand.

Museum lighting design represents a specialised area of architectural design where multiple and often conflicting requirements must be considered simultaneously. Achieving an appropriate balance between daylight quality, conservation requirements, visual comfort, and energy efficiency is therefore a key challenge. Developing knowledge in this area can support future museum projects and contribute to more informed daylighting strategies in Nordic museum environments.

Previous studies have investigated several aspects of daylighting in museum environments, including daylight distribution, glare control, visitor perception, skylight design, and artwork conservation. While these studies have improved the understanding of daylight quality and visual comfort in museums, less attention has been given to how daylight performance relates to energy performance.

Furthermore, relatively few studies evaluate daylight quality, visual comfort, artwork protection, and energy performance within the same assessment framework. This challenge is particularly relevant in Nordic climates, where daylight availability varies significantly throughout the year.

Therefore, this thesis investigates daylight quality, visual comfort, artwork protection, and energy performance in Malmö Konsthall through a combination of simulations, field measurements, and user evaluations.

1.3 Aims and assumptions

This thesis aims to improve the understanding of daylighting in museum buildings, particularly in relation to energy use in the Nordic context. The study focuses on the interaction between lighting and energy performance, highlighting the challenges of balancing daylight quality with energy efficiency in exhibition spaces.

To address this aim, the study assesses daylight and energy performance in a case study museum located in Malmö. Daylight conditions are evaluated using established performance metrics, including Daylight Factor (DF), average illuminance (lux), Spatial Daylight Autonomy (sDA), Useful Daylight Illuminance (UDI), Annual Sunlight Exposure (ASE), and Daylight Glare Probability (DGP), while also examining how daylight design influences electric lighting demand and related energy use.

This study assumes that climate-based daylight metrics can provide meaningful insight into visual performance in exhibition spaces, even though museum environments may require additional interpretation beyond standard thresholds. It is further assumed that combining daylight analysis with energy-related assessment offers a more comprehensive understanding of building performance than studying daylight alone.

The intention is therefore not only to measure daylight levels, but to understand how architectural decisions affect both visual quality and energy performance in museum buildings.

1.4 Research questions

The main objectives of this thesis was to answer the following research questions:

- RQ1. How can daylight conditions in a Nordic museum environment, represented by Malmö Konsthall, be assessed in terms of daylight quality, visual comfort, and energy performance? and what methodology is appropriate for such an assessment?
- RQ2. Is there a relationship between the answers to the questionnaire in the survey and the simulation-based analysis relying on daylight metrics?

Sub-Questions

- RQ3. What are the current daylight conditions in Malmö Konsthall?
- RQ4. How do skylights influence daylight distribution and visual comfort in the exhibition space?
- RQ5. How does daylight design affect overall building energy use, including electric lighting and heating?

2. Literature review

2.1 Daylighting in museum environments

Previous research indicates that the design and typology of daylight openings play a central role in shaping the spatial experience of museum environments. The configuration of side-lighting and top-lighting strategies influences not only daylight distribution, but also the relationship between exhibition spaces and the outdoor environment (Iordanidou, 2017). While top-lighting systems such as skylights often provide more uniform illumination, they may reduce visual connection to the exterior. In contrast, side-lighting can enhance the connection to the outside, although it requires careful control to avoid glare and uneven light distribution.

In the climate of Italy, Collivasone and Gremo (2024) examined lighting design strategies in museum exhibition spaces through a case study of the Egyptian Museum in Turin. The research focuses on how daylight can be reintroduced into gallery spaces while maintaining appropriate lighting conditions for the conservation of artworks. That study combined literature review, on-site observations, and digital lighting simulations using 3D models to evaluate the interaction between daylight and electric lighting. The findings indicate that daylighting can enhance the spatial quality and visitor experience in museums, but it requires careful control through shading systems and lighting design to prevent glare and potential damage to the artwork.

In the climate of Atlanta, Li et al. (2024) examined how skylight design in museum galleries can be improved using simulation tools. The study investigated how different skylight shapes and sizes affect daylight distribution inside the space, as well as glare and direct sunlight on artworks. The results indicated that changing the geometry of skylights can increase useful daylight while reducing problems such as glare and overexposure. The study also suggests that better daylight design can lower the need for electric lighting, which may help reduce energy use in museum buildings.

2.2 Skylights, visual comfort and artwork conservation

A recent study by Dolníková et al. (2025) analyses how different shading strategies influence daylight performance in gallery spaces, with particular attention to roof openings. Through daylight simulations and on-site measurements, the study evaluates parameters such as Daylight Factor (DF), minimum illuminance (E_min), illuminance uniformity (Uo), and daylight glare probability (DGP). The results show that even when minimum DF values are achieved, the quality of daylight strongly depends on how skylights are treated. Certain shading solutions improved light distribution and reduced glare, while others led to uneven lighting or insufficient illuminance under overcast sky conditions. This demonstrates that skylight design is not only about admitting daylight, but also about controlling its intensity and distribution.

Another recent study by Samaniego (2024) shows that different skylight geometries significantly influence daylight perception in museum galleries. Even when illuminance levels are within recommended museum ranges (50–200 lux), the spatial experience can vary depending on how daylight is distributed. In that study, a monitor-type skylight created stronger contrasts with brighter central areas and darker edges, while a baffle-type skylight resulted in a more uniform light distribution.

2.3 Daylight and energy performance

When analyzing daylighting in museum buildings, it is important to understand the connection between light quality and energy use. Ismail et al. (2024) show that architectural factors, such as building form, mass variations and window-to-wall ratios, can have a stronger impact on daylight performance and thermal energy load than technical systems alone. In their study, sDA and ASE were calculated as the main daylight metrics, and the results showed_that it is possible to achieve high sDA values (around 80%) while keeping ASE below 10%, if the building geometry and glazing ratios are carefully adapted to the climate. The authors also explained that different climates require different strategies. In hot climates, self-shading forms are more effective to reduce overheating and excessive sunlight, while in moderate and cold climates, glazing ratios and daylight access become more important. This means that daylighting design in museums is not only about bringing in as much daylight as possible, but about controlling the amount and distribution of light through architectural design decisions.

2.4 Daylighting in Nordic museum environments

Research conducted in Nordic museum contexts suggest demonstrates that perceived brightness does not necessarily correspond to measured daylight performance. In the case of Medelhavsmuseet in Stockholm, Sweden, simulations revealed limited daylight sufficiency over time, despite the presence of large skylights, whereas visitor perception was strongly influenced by electric lighting and seasonal conditions (Madhoon, 2019). These findings highlight the importance of combining quantitative daylight simulations with qualitative perception-based evaluation.

3. Methodology

This thesis uses a case study approach, with Malmö Konsthall selected as the study object. The building was chosen because daylight is a key architectural feature using large skylights and façade windows. This makes the building suitable for studying daylight quality, visual comfort, and energy-related aspects in a Nordic museum context.

The methodology combines simulation-based analysis, field measurements, and visitor surveys to provide both objective and subjective assessments of the museum environment. Daylight simulations were used to evaluate daylight availability, glare, and illuminance conditions, while energy simulations were conducted to assess the impact of daylight-related design strategies on building energy performance. Field measurements and survey responses were used to complement the simulation results and provide insight into actual lighting conditions and visitor perceptions. Figure 1 presents an overview of the methodological framework applied in this study.

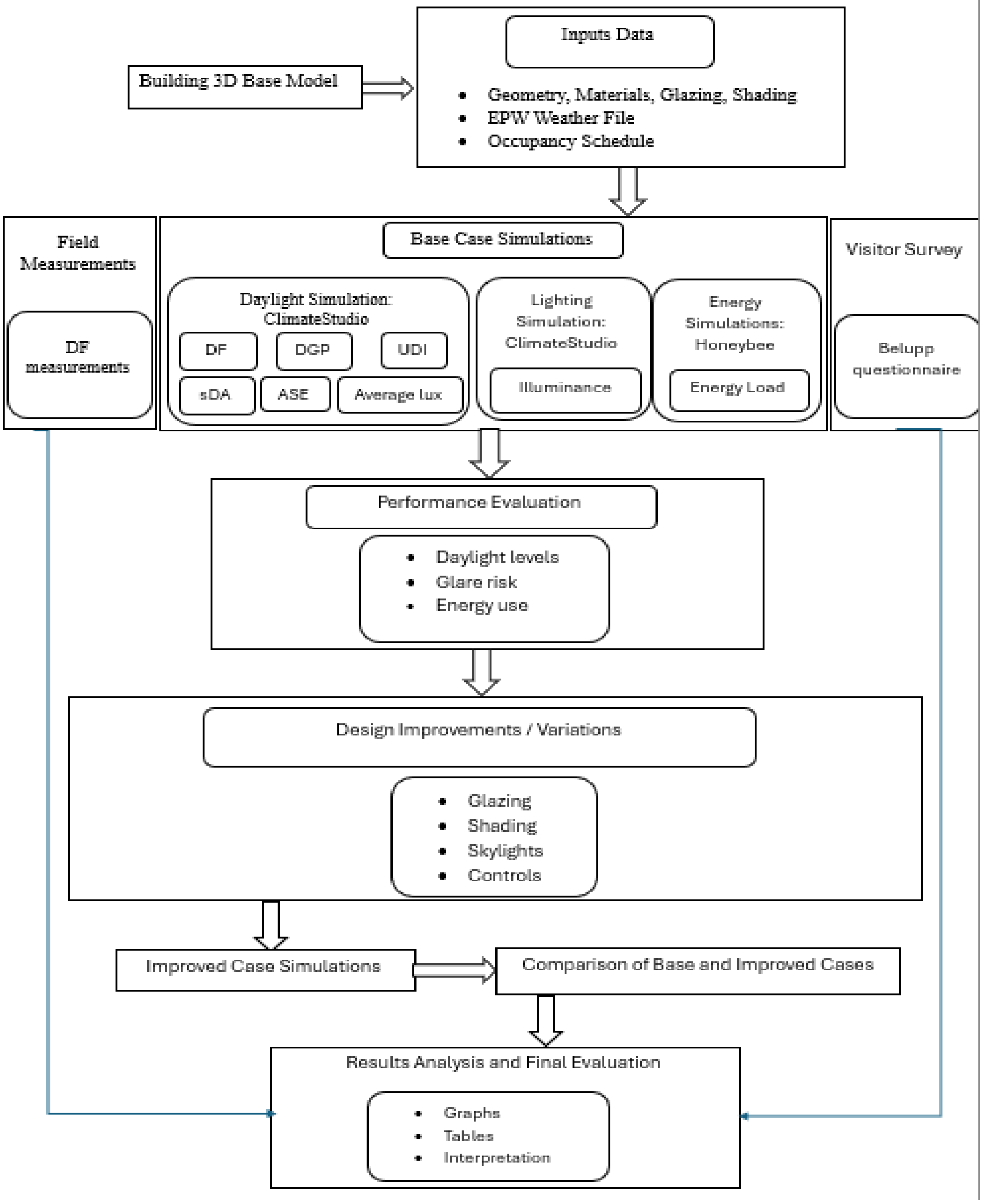


Figure 1: Research methodology

3.1 Site analysis

Malmö Konsthall is situated in central Malmö at 55.6° N and 13.0° E, placing it in southern Sweden (See Figure 2). The Nordic climate at this latitude results in strong seasonal differences in daylight availability. Winters are characterized by limited daylight hours, a dominance of dark overcast skies, and low solar angles, a dominance of dark overcast skies, while summers provide extended daylight periods. These variations must be considered when evaluating daylight performance in the building.

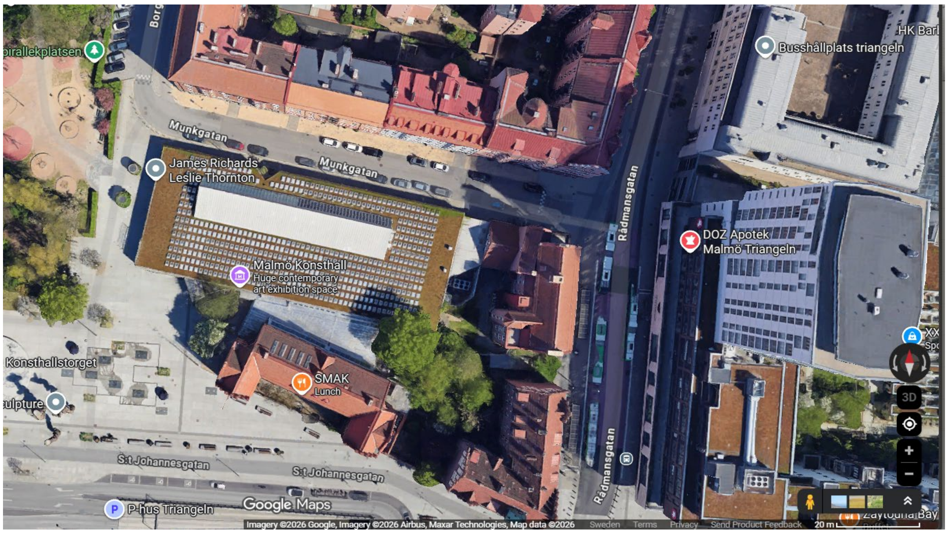


Figure 2. Location of Malmö Konsthall and its surrounding urban context (Source: Google Maps)

The overall layout of the exhibition hall is large, rectangular, and open-plan. The roof plan illustrates the arrangement of the saw-tooth skylights that play a key role in the daylighting strategy (see Figure 3). According to the site orientation, the primary glazed façade faces west (see Figure 4). This orientation allows sunlight to enter the space later in the day, especially during afternoon hours, which may result in higher illuminance levels and increased risk of glare in areas close to the façade.

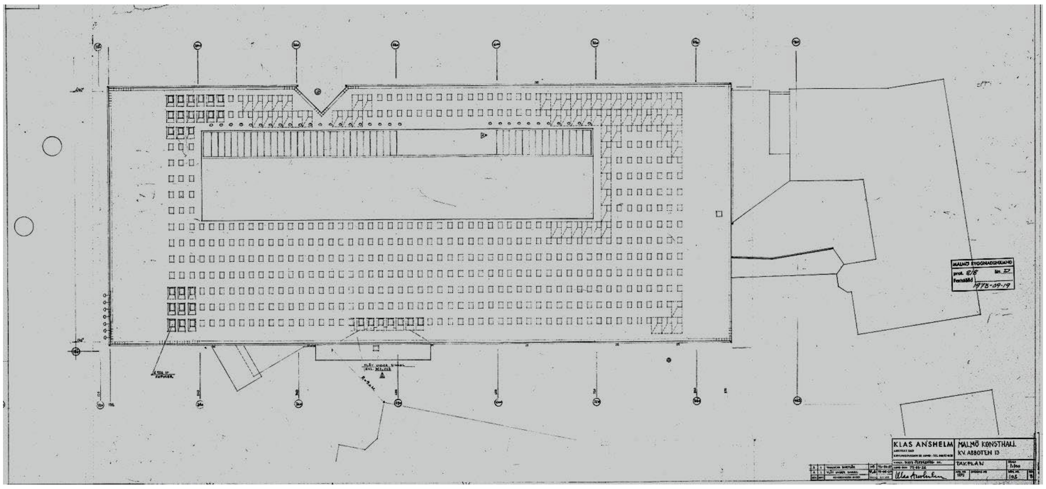


Figure 3. Roof plan of Malmö Konsthall (Source: Stadsbyggnadskontoret Archive, Malmö). Documaster C-Archive

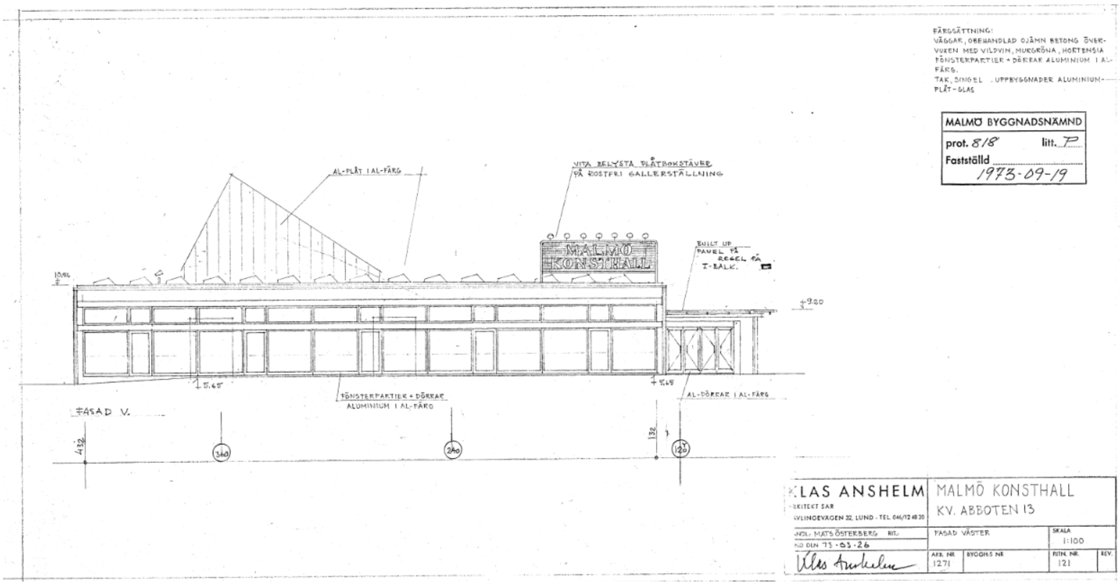


Figure 4. West façade of Malmö Konsthall (Stadsbyggnadskontoret Archive, Malmö). Documaster C-Archive

A defining architectural feature of the building is its roof structure, which consists of repeated north-facing skylights arranged in a saw-tooth configuration (see Figure 5). These roof elements are designed to admit mainly diffuse daylight from the north, reducing the amount of direct solar radiation entering the hall. This strategy supports a more uniform distribution of daylight across the space and contributes to improved visual comfort.

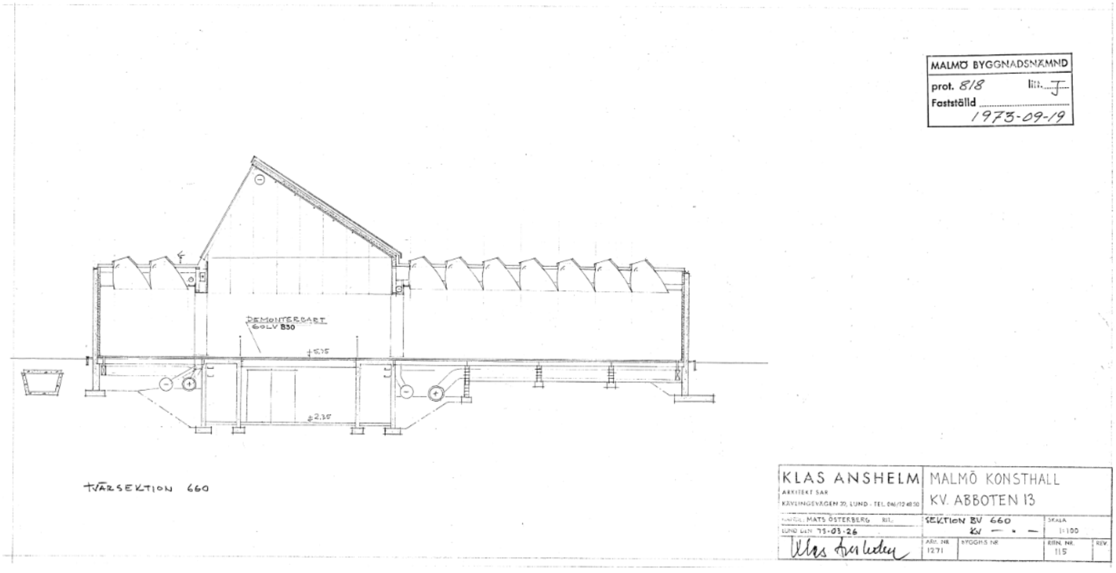


Figure 5. Section of Malmö Konsthall (Stadsbyggnadskontoret Archive, Malmö). Documaster C-Archive

The daylighting concept of Malmö Konsthall was developed by architect Klas Anshelm and is based on the use of north-facing saw-tooth skylights that provide diffuse daylight to the exhibition space. This strategy was intended to create a bright and visually comfortable environment while reducing direct solar exposure on artworks.

The behaviour of daylight within the skylight structure can be observed in Figure 6, where light is reflected and diffused across the internal surfaces before reaching the exhibition space. This indirect light path helps to soften contrasts and reduce the risk of glare.

Figure 6. Interior view of the saw-tooth skylights showing diffuse daylight and internal reflections within the roof structure (author's own photograph)

The interior environment includes high ceilings and light-coloured surfaces, which enhance daylight distribution and support deeper daylight penetration (see Figure 7). However, the flexible exhibition layout means that temporary partitions can influence how daylight is distributed within the hall (see Figure 8).

Figure 7. Interior view showing high ceilings and light-coloured surfaces enhancing daylight penetration (author's own photograph)

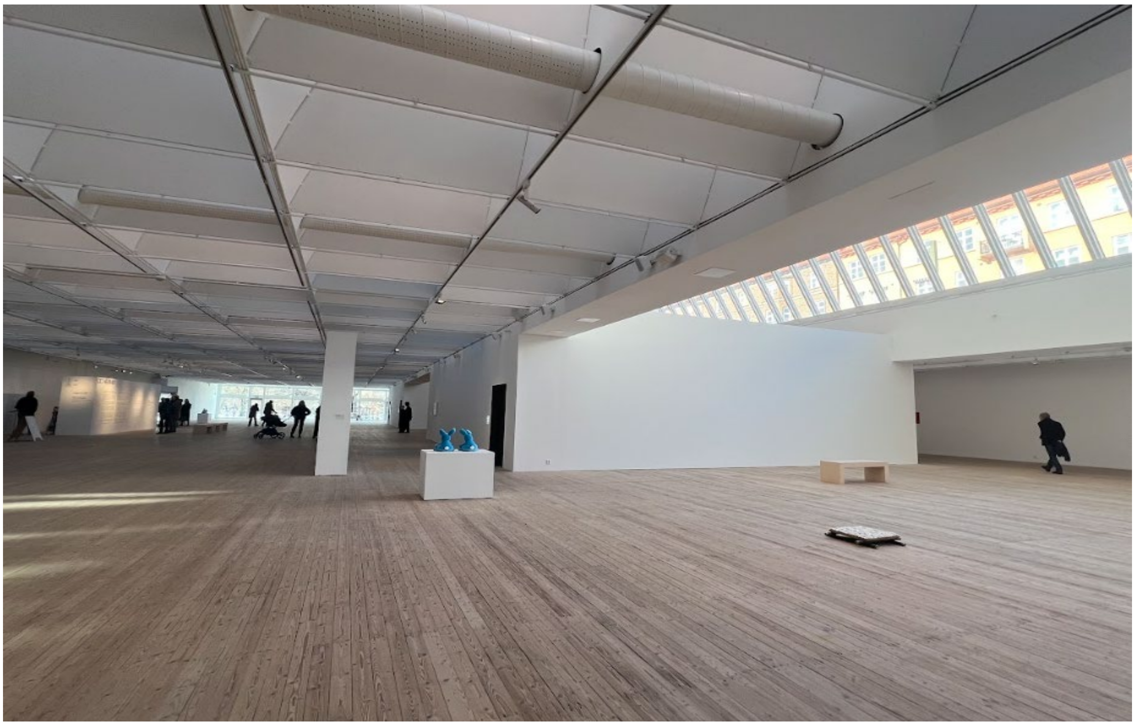


Figure 8. Interior view illustrating the open exhibition space and the influence of layout and internal elements on daylight distribution (author's own photograph)

The combination of vertical west glazing and north-oriented roof lighting creates a dual daylight strategy. This makes Malmö Konsthall particularly suitable for studying daylight distribution, glare conditions, and visual comfort within a museum context in a Nordic climate. Additional photographs from the site visit documenting the exhibition spaces, skylight systems, façade glazing, and daylight conditions are presented in Appendix B.

The Figure 9 and Figure 10 below presents the simulation model of Malmö Konsthall developed in Rhino. They illustrate the geometry of the building and the setup used for the daylight analysis.

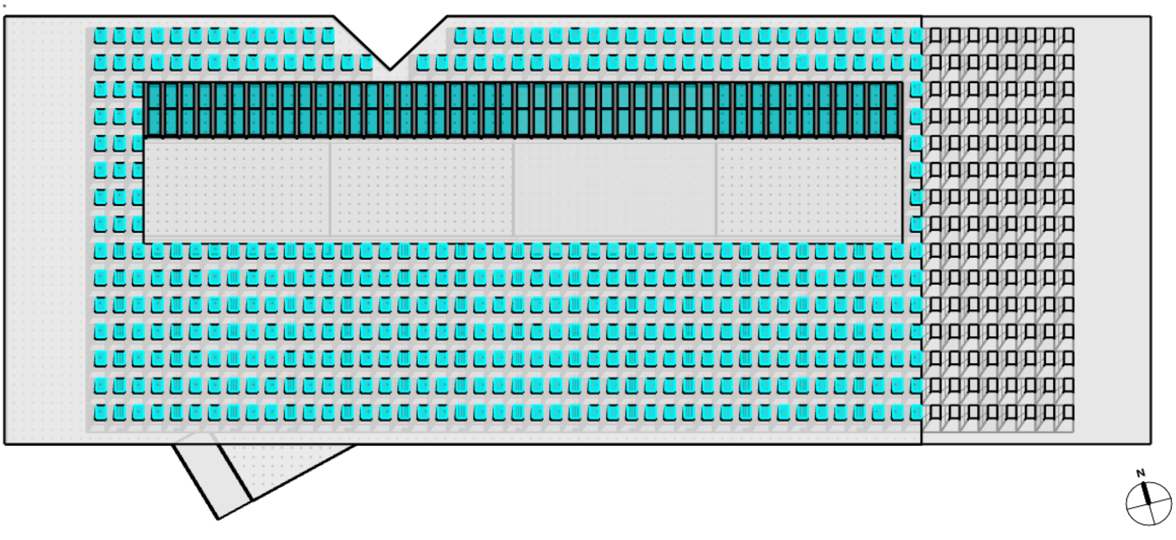


Figure 9. Plan layout of Malmö Konsthall showing the distribution of skylights, as modelled in Rhinoceros

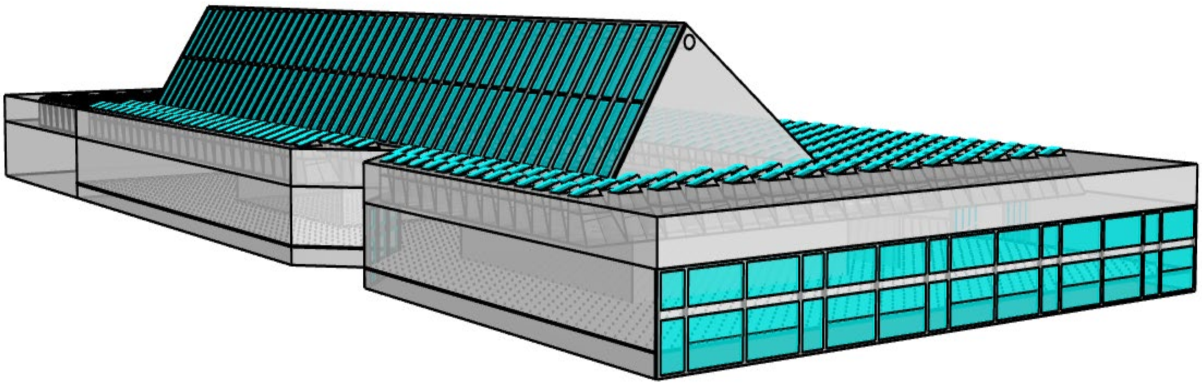


Figure 10. Three-dimensional model showing the skylight configuration of Malmö Konsthall, as modelled in Rhinoceros

3.2 Climate data and weather file

A typical meteorological year weather file in EPW format for Malmö, Sweden, was used in this study. The file was obtained from the Ladybug Tools climate data library, based on long-term measured weather data.

After importing the EPW weather file into Grasshopper, the Ladybug Tools were used to extract the local illuminance conditions. The daylight simulation inputs included direct normal illuminance (DNI), diffuse horizontal illuminance (DHI), and global horizontal illuminance (GHI), which together describe the luminous characteristics of the outdoor environment. Figure 11 shows that direct normal illuminance is particularly high between May and August, with elevated values occurring approximately between 06:00 and 18:00. This indicates that during summer months, large skylight areas may increase the risk of glare due to strong direct sunlight.

Diffuse horizontal illuminance (DHI) in Malmö also peaks between May and August. Typical overcast conditions are associated with DHI values between 10,000 and 25,000 lux (Khan, 2025). The annual pattern suggests that Malmö experiences predominantly overcast sky conditions, with seasonal periods of increased diffuse brightness. Global horizontal illuminance (GHI) exhibits a pronounced seasonal variation. During summer, peak GHI values can reach approximately 86,500 lux, reflecting both high solar altitude and extended daylight hours at Malmö’s northern latitude. In contrast, winter illuminance levels remain low, with DHI frequently below 5,000 lux, indicating consistently dim and overcast conditions.

Overall, the illuminance analysis highlights the strong seasonal contrast in daylight availability. High summer illuminance levels, combined with long daylight hours, suggest that buildings in this region may require appropriate shading strategies to mitigate glare and reduce unwanted solar heat gains, while winter conditions emphasize the need for efficient electric lighting.

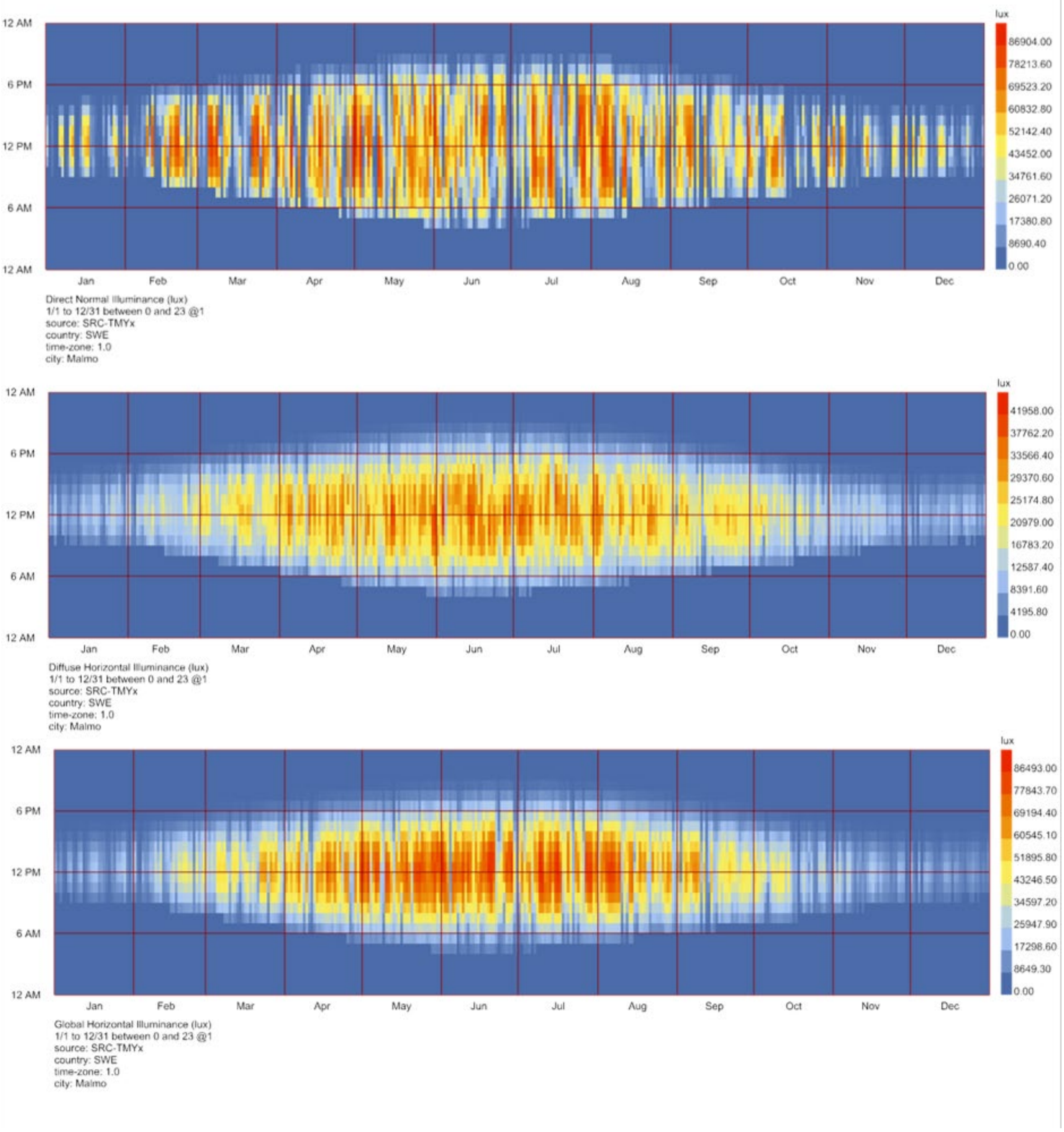


Figure 11. Direct normal, diffuse horizontal and global horizontal illuminance in Malmo (lux), source: run by Ladybug

3.3 Quantitative methods

A model of the selected exhibition spaces was created based on available architectural drawings and on-site observations. The computer programs used in this study include Rhinoceros, ClimateStudio, Ladybug Tools, and Grasshopper. The details of the software and versions used are presented in Table 1. ClimateStudio relies on two established simulation engines: Radiance for lighting analysis and EnergyPlus for energy modeling. Radiance is a physically based ray-tracing engine that has been extensively validated within academic research and is widely regarded for its accuracy in daylight simulation. EnergyPlus supports the platform's energy analysis due to its proven reliability and its comprehensive capabilities as a whole-building energy simulation tool.

Table 1: Software used in the study and their functions

Software	Version	Description
Rhinoceros	8 SR25 (v8.25.25314)	The primary 3D modeling platform used to develop the building geometry.
ClimateStudio	v2.3.9530	The plugin within both Grasshopper and Rhino. The plugin in Rhino 8 is used for environmental lighting simulation. The plugin in Grasshopper is used for energy simulation.
Grasshopper	Build 1.0.0008	The integrated visual programming environment within Rhino utilized for parametric control.
Ladybug	v1.9.0	A plugin for Grasshopper used to import and analyse climate data (EPW files) and to visualize environmental conditions such as solar radiation and illuminance.

Daylight performance is evaluated using common daylight metrics, including DF, DGP, UDI, sDA, ASE, and avg lux. These metrics are used to analyse daylight availability, daylight distribution, and potential glare under different daylight conditions. If access allows, simple on-site illuminance measurements (lux) are carried out to support and check the simulation results.

3.3.1 Daylight and lighting indicators used in this study

In this study, different indicators are used to evaluate daylight, glare and lighting energy. These indicators are based on European standards, mainly SS-EN 17037, SS-EN 12464-1 and SS-EN 15193-1.

Daylight Factor (DF)

"The daylight factor is defined as the ratio of horizontal indoor to outdoor illumination by daylight under continuously overcast sky conditions, expressed as a percentage." (Müeller, 2013, p. 236). It is calculated as:

$$DF = E_{i}n/E_{o}ut \times 100 \tag{1}$$

There are different ways to assess DF depending on the level of detail. The point daylight factor (DFp) is based on a single measurement taken at a fixed position in the room, typically 1 m from the darkest wall, halfway into the room, and at a height of about 0.8 m above the floor. This approach was used in older Swedish standards, but it is quite limited since it only represents one location and does not describe the overall daylight conditions in the space. A more reliable approach is the median daylight factor (DFmedian), which is calculated using several points distributed across the room. It represents the middle value of all measurements and is less affected by unusually high or low values. Because of this, it gives a clearer picture of how daylight is spread within the space and is therefore more suitable for evaluation in design practice (Dubois et al., 2025, p. 183-184).

Even though DF is still commonly used in Sweden as a basic indicator, it is based on fixed conditions and does not show how daylight varies over time. For this reason, it is often used together with more advanced daylight evaluation methods.

Daylight Provision Levels

According to SS-EN 17037, daylight performance is assessed using target illuminance levels that must be achieved across both space and time. The standard defines three performance levels (minimum, medium, and high), where the required illuminance should be met in at least 50% of the utilised floor area. In addition, the time aspect is considered, meaning that these illuminance levels should be achieved for at least 50% of the daylight hours over the year. This approach ensures that the evaluation reflects not only how daylight is distributed in the space, but also how consistently it is available over time. The daylight provision levels are summarised in Table 2.

Table 2: Daylight provision values

Performance Level	Target Illuminance (lux)	Area Requirement	Temporal Requirement
Minimum	300	50% of floor area	50% of daylight hours
Medium	500	50% of floor area	50% of daylight hours
High	750	50% of floor area	50% of daylight hours

Glare (Daylight Glare Probability – DGP)

Daylight glare is commonly evaluated using the Daylight Glare Probability (DGP), developed by Wienold and Christoffersen to address the limitations of earlier glare indices such as Daylight Glare Index (DGI), and CIE Glare Index (CGI). These indices were originally based on electric lighting conditions and showed weak performance when applied to daylight from windows. To overcome this, the authors conducted experimental studies combining luminance measurements with subjective glare evaluations under real daylight conditions. By comparing measured data with user responses, they identified vertical eye illuminance as a key factor influencing glare perception. Based on these findings, the DGP model was developed to include vertical eye illuminance together with characteristics of glare sources, such as luminance, size, and position within the field of view. This approach established a strong relationship between physical lighting conditions and perceived glare, making DGP a reliable indicator for daylight environments (Wienold & Christoffersen, 2006).

In addition to the DGP model, SS-EN 17037 provides recommendations for acceptable glare conditions over time. The standard states that high glare levels should occur only during a limited portion of the occupied period. Specifically, DGP values should not exceed defined thresholds for more than 5% of the occupied time, ensuring that visual discomfort remains infrequent and acceptable. To support different design objectives, the standard defines three levels of glare protection, each associated with a corresponding DGP threshold. Lower DGP values indicate stricter glare control and higher visual comfort. The classification of glare perception based on DGP values is presented in Table 3.

Table 3: Daylight Glare Probability (DGP) ranges and corresponding glare perception (after Tregenza & Wilson, 2011, as cited in Dubois et al., 2025)

DGP Value	Glare Perception
< 0.35	Imperceptible glare
0.35–0.40	Perceptible
0.40–0.45	Disturbing
> 0.45	Intolerable

Useful Daylight Illuminance (UDI)

The Useful Daylight Illuminance (UDI) metric is used to evaluate whether daylight levels fall within a range that is considered beneficial for indoor environments. Instead of only assessing whether daylight is sufficient, UDI divides illuminance levels into different categories based on their usefulness.

Daylight levels between 100 and 3000 lux are generally considered useful. Within this range, values between 100 and 300 lux represent a lower useful range, where daylight may still need to be supplemented with electric lighting. Values between 300 and 3000 lux are typically considered optimal, as they provide sufficient illumination for most visual tasks without causing discomfort. Illuminance levels below 100 lux indicate insufficient daylight, while values above 3000 lux may lead to visual discomfort, or excessive brightness (Dubois et al., 2025).

Spatial Daylight Autonomy (sDA)

The Spatial Daylight Autonomy (sDA) is used in building certification systems such as LEED to evaluate daylight performance. According to LEED v4 Option 1, daylight is assessed using annual simulations, where $sDA_{300/50\%}$ represents the percentage of regularly occupied floor area that receives at least 300 lux for at least 50% of the occupied hours. Based on this evaluation, points are awarded depending on how much of the space meets the required daylight level. Achieving sDA values above 55% of the floor area can provide 2 points, while reaching values above 75% can provide 3 points. This shows that higher daylight availability across the space leads to better performance ratings in the certification system (Solemma, n.d.).

Annual Sunlight Exposure (ASE)

Annual Sunlight Exposure (ASE) is used to assess the risk of excessive direct sunlight in indoor environments. It was introduced as a complementary metric to Spatial Daylight Autonomy (sDA) and focuses on identifying areas that are exposed to high levels of direct sunlight for extended periods. The commonly used indicator, $ASE_{1000,250h}$, represents the percentage of points in a space that receive more than 1000 lux of direct sunlight for at least 250 hours per year. Based on this metric, different performance levels can be identified. Spaces where more than 10% of the area exceeds this threshold are considered to have a high risk of visual discomfort. Values below 7% are generally acceptable, while values below 3% indicate good daylight conditions with limited risk of excessive sunlight (Dubois et al., 2025, p. 192-193).

ASE is also applied in building assessment systems such as LEED and WELL, where it is used to control excessive sunlight exposure. However, the interpretation of ASE should consider the building context. However, ASE should be interpreted carefully in Nordic climates, where daylight availability changes greatly between summer and winter.

Lux hours (Light exposure)

In museum environments, light exposure is often evaluated using the concept of lux hours, which combines the light level and the time of exposure. According to LedaPlus (n.d.), the total light exposure can be calculated using the following formula:

$$Exposure\ (lux\ hours) = Light\ level\ (lux) \times Time\ (hours) \tag{2}$$

This means that both the intensity of the light and the duration of exposure determine the total light dose received by an artwork. According to the example presented in the article, 1 hour of direct sunlight at 100,000 lux results in 100,000 lux-hours of exposure. The same total exposure can also occur in a museum gallery where the light level is much lower, but the exposure time is longer. For instance, 2,000 hours at 50 lux also results in 100,000 lux hours (LedaPlus, n.d.) This example illustrates that light damage is cumulative, meaning that a short exposure to very strong light can produce the same total exposure as a long period under weaker lighting. High illuminance levels may lead to damage over time, as light exposure is cumulative and depends on both intensity and duration (ERCO, Damage of Museum Objects by Light, n.d.).

In addition to controlling the illuminance level, museums also manage the total annual light exposure. For example, highly sensitive objects are recommended to receive no more than 100,000 lux-hours per year, while moderately sensitive objects may receive up to 450,000 lux-hours per year (Museums Galleries Scotland, 2024).

Illuminance levels in museums

Illuminance is defined as the density of illumation (lumen/m^2) incident on a surface and is measured in lux (1 lux = 1 lumen/m^2). It is commonly used to evaluate whether lighting conditions are sufficient for visual tasks. However, higher illuminance levels do not necessarily indicate better lighting quality, as excessive light may lead to glare and visual discomfort. Therefore, both the quantity and distribution of light should be carefully considered, especially in environments where visual comfort is important (Tunku Abdul Rahman University College, 2020). In this study, illuminance values are based on an annual daylight simulation.

In museum environments, illuminance levels measured in lux are usually determined according to how sensitive objects are to light damage. Highly sensitive materials such as photographs, paper, textiles, and watercolours are typically displayed at around 50 lux to prevent fading and deterioration. Objects with moderate sensitivity, including oil paintings, wood, and leather, can generally tolerate light levels of about 200 lux. Materials that are considered relatively insensitive to light, such as stone, metal, glass, or ceramics, may be displayed at up to 300 lux.

In museum environments, lighting design is not only concerned with providing sufficient visibility but also with controlling the amount of light reaching the artworks. The actual illuminance on an object is influenced by several interacting factors, including the intensity of the light source, the transmission properties of display elements such as glass, and the reflectance characteristics of the artwork itself. This means that the light perceived by visitors is not equal to the incident light, but rather the result of a filtered and reflected process. Therefore, both the material properties and the display conditions play a significant role in determining the final lighting conditions, making careful control of these parameters essential to reduce potential light-induced damage while maintaining visual clarity (Domoticware S.L.U., 2010). The recommended illuminance levels for museum are presented in Table 4.

Table 4: Recommended Illuminance Levels for Museum Objects (Museums Galleries Scotland, 2024)

Type of artwork / material	Sensitivity to light	Recommended illuminance (lux)	Maximum annual exposure (lux·h/year)
Photographs, paper, textiles, watercolours	High sensitivity	around 50	up to 100,000
Oil paintings, wood, leather	Medium sensitivity	up to 200	up to 450,000
Stone, metal, glass, ceramics	Low sensitivity	up to 300	not limited (can tolerate high exposure)

Maintained illuminance (Electric lighting)

Electric lighting is evaluated using maintained illuminance (E_m), according to SS-EN 12464-1:2021. This means the minimum average illuminance level that should be maintained in the space. According to this Standard, the typical value for exhibition or display areas is from 300 to 500 lux.

LENI – Lighting Energy Numeric Indicator

To connect lighting with energy use, the Lighting Energy Numeric Indicator (LENI) is used. LENI shows the annual lighting energy use per square meter expressed in kWh/m²·year. The LENI depends on installed lighting power, operating time and daylight dependency, as explained in SS-EN 15193-1:2017. Table 5 presents the input parameters and corresponding values applied in the LENI calculation.

Table 5: Parameters input in LENI calculation

Parameter	Values
Control function factor	1.00
Occupancy dependency factor	1.00
Daylight supply factor	0.68
Lighting control factor	0.85
Daylight dependency factor	0.42
Constant illuminance dependency factor	1.00

3.4 Data analysis and synthesis

The results from daylight simulations, on-site measurements, architectural analysis, and visitor surveys were analyzed collectively. Integrating these methods enables a comparison between objective daylight performance metrics (both measured and simulated) and the subjective perceptions reported by visitors. This combined approach provides a comprehensive understanding of daylight-related issues in the exhibition space and supports the identification of potential improvement strategies.

3.4.1 On-site measurement

The measurement was taken on 20th March 2026, with an overcast sky. The indoor illuminance (E_{in}) at each measurement point was recorded using a calibrated digital lux meter (Hagner EC1 X lux meter, which offers 0.1 lux resolution and an accuracy of about ±3%).

Figure 12. Hanger ECI-X lux meter used for on-site measurements (source: Hagner AB, 2026)

To determine the corresponding outdoor illuminance (E_{out}), a second lux meter was placed simultaneously in an unobstructed exterior location. The DF at each point was then calculated using the standard Equation (1). However, because the lighting control system could not be accessed during the measurement period, all electric luminaires remained fully activated. Under these conditions, the same computational procedure should be applied to derive the Combined Illuminance Ratio rather than the DF.

The instrument was placed at a height of 0.8 m above the floor, with its sensor directed toward the ceiling. A non-symmetric diagonal compensation layout was implemented for sensor placement. Due to spatial constraints, a modified measurement grid was applied, consisting of a diagonal arrangement combined with a central horizontal line (Figure 12).

Due to site-specific constraints and the presence of internal structural elements, such as partitioned zones and wall segments, a customized measurement transect was applied instead of a conventional diagonal or uniformly spaced grid (Figure 13). During the measurement period, the electric lighting system was operating under normal exhibition conditions. Although the sky was predominantly overcast, intermittent variations in cloud cover were observed, which may have influenced the recorded illuminance values.

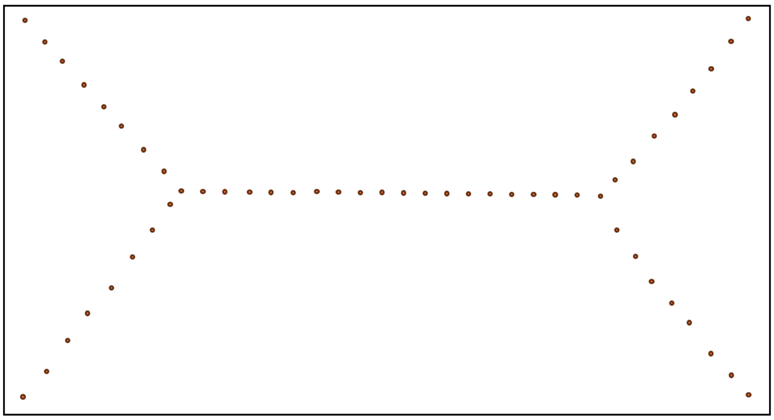


Figure 13. Sensor placement

The primary objectives of the Combined Illuminance Ratio measurements in this study are threefold. First, they aim to compare the measured values with the simulation results in order to validate the accuracy of the modeling environment. Second, they provide an assessment of daylighting performance under real operating conditions. Third, they enable a comprehensive examination of how the luminous environment influences user perception when interpreted alongside synchronized questionnaire responses. It should be noted that the measurements were conducted under actual operational conditions, with electric lighting active.

A limitation of the measurement campaign is that the electric lighting system remained in operation during the measurements. Consequently, the measured illuminance values represent the combined effect of daylight and electric lighting rather than daylight alone. Therefore, the measurements were used primarily to compare the overall luminous environment with simulation outputs and survey responses rather than as a strict validation of daylight factor calculations.

3.4.2 Questionnaire

The questionnaire used in the visitor survey is adapted from BELUPP (Building Environmental Lighting User Perception Project) (Parvathy et al., 2023), which is provided in Appendix A. BELUPP is a validated survey tool developed to assess users' subjective perceptions of lighting environments and has been widely applied in post-occupancy evaluations. It was selected for this study because it provides a structured method for evaluating how people experience lighting quality and allows comparison between subjective perceptions and objective daylight performance metrics. The survey employs a seven-point semantic differential scale (e.g., dark–bright, warm–cool), where each pair of opposing adjectives represents a specific perceptual dimension of lighting.

Participants were recruited on-site on 20th March 2026. A convenience sampling method was used, selecting participants who were present at the site during the study period. Participants including both staff and visitors were asked to rate their experience by selecting a position between each pair of contrasting terms. This method captures nuanced perceptions of the lighting environment and allows the results to be interpreted across multiple perceptual dimensions.

After the responses were collected, the results for each attribute were aggregated and interpreted according to the scoresheet as presented in Table 6. The scales uses a 7-point semantic different system. In Table 6, the checkbox symbol denotes the raw score (ranging from 1 to 7) selected by each participant. To standardize the interpretation of lighting-quality evaluations, higher numerical values are defined to represent more favorable lighting conditions. For descriptors with negative connotations, the transformation 8 − □ is applied as a reverse-scoring procedure. For instance, if a participant assigns a score of 2 to unpleasant, the corresponding reverse-scored value becomes 6, which aligns with the positive descriptor pleasant. This scoring framework enables a systematic evaluation of the overall lighting experience and supports meaningful comparisons between subjective assessments and objective daylight-performance indicators.

Table 6: Scoresheet for survey, source: Küller & Wetterberg, 1993

	Hedonic tone	**Brightness**	**Variation**	**Colour**	**Flicker**
Light		□			
Unpleasant	8-□				
Coloured				□	
Weak		8-□			
Concentrated			8-□		
Cool	8-□				
Even distrib			□		
Soft	□				
Focused			8-□		
Unnatural	8-□				
No flicker					8-□
Drab		8-□			
Monotonous	8-□				
Sharp	8-□				
Shaded	□				
Brilliant		□			
Good	□				
Sum	:8	:4	:3	:1	:1
Mean					

The evaluation framework is organized into five perceptual dimensions. The first dimension, hedonic tone, refers to the emotional valence experienced by individuals within space. It captures the degree of pleasure, comfort, and psychological well-being elicited by the lighting environment (Scott, 2001). Although hedonic tone is not traditionally included among standard metrics in illuminating engineering, it serves as an important intermediary construct linking objective lighting parameters with human perceptual and emotional responses. A higher hedonic-tone value indicates more positive affective feedback from occupants, thereby offering insight into the experiential dimension of the luminous environment.

The second dimension, brightness, assesses the perceived illumination level of the space. This dimension reflects whether the lighting provides sufficient visual clarity and supports accurate identification of objects. The third dimension, variation, describes the degree of diversity or fluctuation in the lighting environment, which may arise from spatial configuration, daylight penetration, or the distribution of luminaires (Yazdi, 2018).

A fourth dimension, colour, evaluates the tonal characteristics of the light. In museum settings, cooler colour tones are often recommended because they minimize emotional interference and support accurate visual perception of artworks (Revantino et al., 2018).

The final dimension, flicker, concerns the presence of rapid fluctuations in light intensity over short time intervals. Detectable flicker can negatively affect visual comfort and may lead to fatigue or discomfort for occupants.

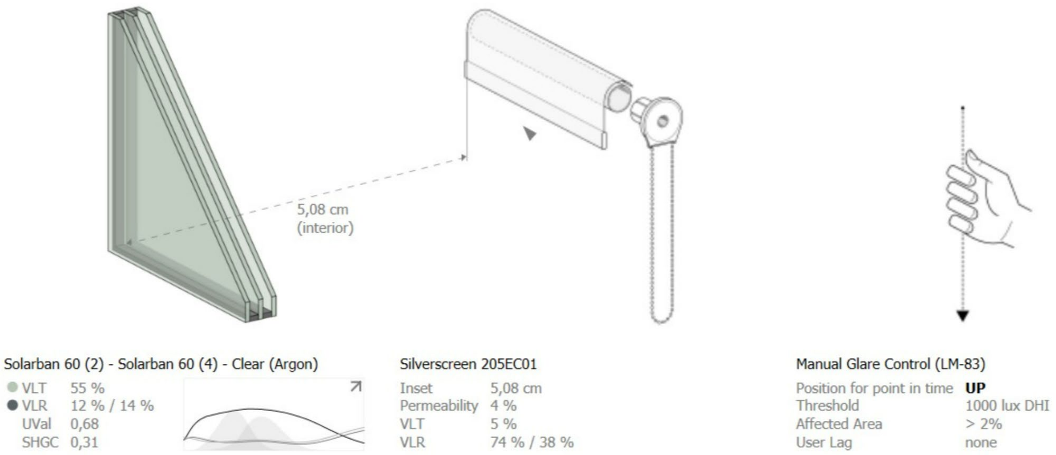
3.5 Daylight simulation

The daylight simulation was conducted in Climate Studio. Information about material inputs used in the simulation is presented in Table 7.

Table 7: Surface material properties used in the daylight simulation

Layer	Material	Visible Light Transmittance (VLT)	Visible Light Reflectance (VLR)
Wall	Dupont White	-	0.84
Ceiling	Dupont White	-	0.84
Floor	Wood Maple	-	0.36
Vertical glazing	Solarban-Solarban-Clear (Argon) (Figure 14)	0.55	-
Skylight glazing	Solarban-Solarban-Clear (Argon) (Figure 14)	0.55	-
Surroundings	Red brick exterior wall	-	0.14

The glazing and shading properties were defined based on values available in the Climate Studio material library (Figure 14). These parameters were not measured on site but selected to represent typical performance of glazing systems with solar control and internal shading devices. The chosen values were considered appropriate for the case study based on available product data and standard material properties.



Solarban 60 (2) - Solarban 60 (4) - Clear (Argon)
● VLT 55 %
● VLR 12 % / 14 %
UVal 0,68
SHGC 0,31

Silverscreen 205EC01
Inset 5,08 cm
Permeability 4 %
VLT 5 %
VLR 74 % / 38 %

Manual Glare Control (LM-83)
Position for point in time **UP**
Threshold 1000 lux DHI
Affected Area > 2%
User Lag none

Figure 14. Glazing and shading properties assigned to the façade glazing in the base

The shading control was defined as manual glare control, and the shading material was specified as Silverscreen 205EC01. Both the control and material were selected from Climate Studio's default library. The redering parameters used for the simulations in Climate Studio are presented in Table 8.

Table 8: Rendering parameters

Parameters	Input
Ambient bounces (-ab)	6
Ambient sample (-as)	4096
Weight limit (-wl)	0.01
CFS Reflections	Applied

3.6 Method for evaluating illuminance on artworks

To evaluate the light exposure on artworks, a set of representative points was defined at the positions of selected artworks within the exhibition space. These points were placed at typical display locations, such as on walls and freestanding elements, at heights corresponding to the centre of the artworks (approximately 1.2–1.5 m above the floor). Figure 15 illustrates the locations of the selected artworks and representative evaluation points used for the annual illuminance assessment.

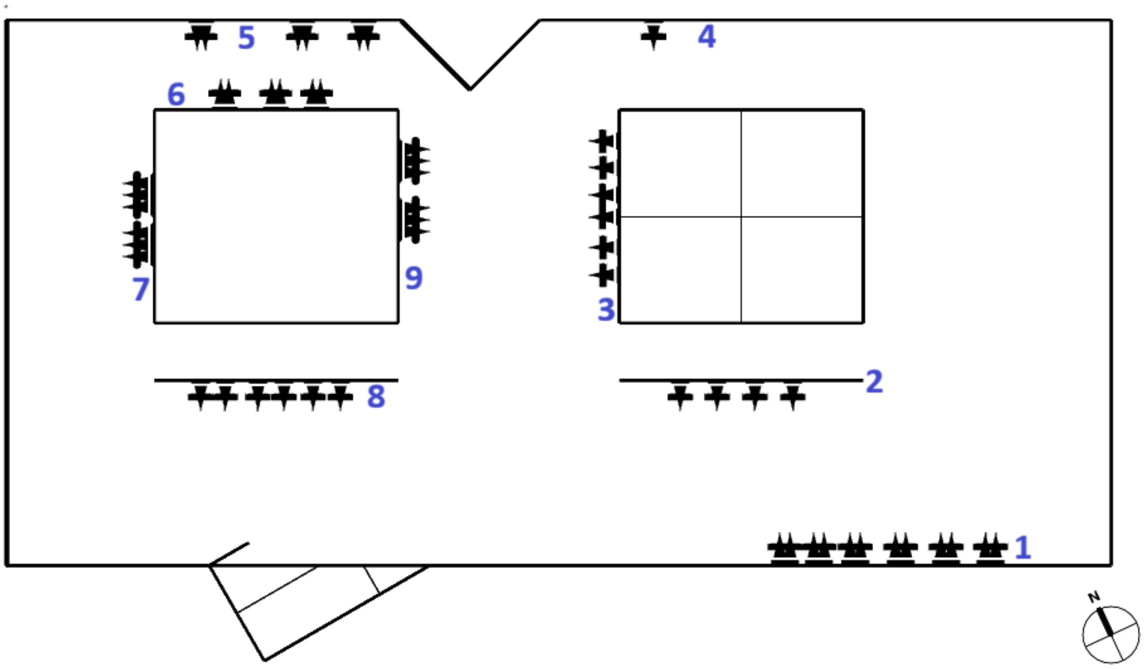


Figure 15. Layout of artwork placement within the exhibition space, showing the spatial distribution of analysed artworks (1–9)

Annual climate-based daylight simulations were then performed to calculate the average illuminance (lux) at each point over the year. The analysis was based on the defined occupancy schedule 11:00–17:00 (closed on Mondays), ensuring that the results reflect typical exhibition conditions.

The selected points allow for a spatial comparison of light exposure across the exhibition space and make it possible to identify areas with higher or lower illuminance levels. This approach also enables the assessment of potential risks related to excessive light exposure in relation to conservation guidelines.

3.7 Energy simulation

After constructing the building model in Rhino, the daylight and energy simulations were carried out in Grasshopper using the ClimateStudio plugin. Relevant architectural and operational information about the museum is summarized in Table 9. Some input values, such as people density, equipment load, and heating set point, were assumed due to the lack of detailed data from the museum. It should be noted that the heated floor area used in the energy simulation includes the enclosed room within the museum. However, this room was excluded from the daylight simulation, as it does not receive any daylight and therefore does not contribute to the daylighting analysis.

The information about the ventilation system, heat recovery, and heating provision were not obtained from the museum. As a result, the simulation was carried out using the default ventilation and heat-recovery parameters provided by ClimateStudio. These default values follow standard assumptions for mechanically ventilated buildings and allow the thermal model to operate consistently, although they do not reflect the exact specifications of the HVAC system in museum. These assumptions introduce a limitation to the accuracy of the energy simulation results.

Lighting Power Density (LPD) is used to describe how much electrical power is needed for lighting in a building relative to its floor area. It gives an idea of the installed lighting load and is often used to evaluate and compare energy performance.

For museum buildings, ASHRAE Standard 90.1 suggests an LPD value of 0.55 W/ft² (around 5.9 W/m²) using the building area method (Enlighted, 2022). In this study, this value is used as a reference to assess and compare the lighting energy results obtained from the simulations.

Table 9: Simulation input for energy simulation

Parameter	Value
Heated floor Area (m2)	1674.6
Average Visitors (per day) *	50
Opening hours	11am to 5pm (closed on Monday)
Cooling	Off
People Density (persons/m2)	0.03
Equipment Density (W/m2) *	5
Lighting Density (W/m2)	22
Heating set point (°C) *	20

Information about the electric lighting system is presented in Table 10. The wattage and lumen of each luminaire were provided by the museum, while the total number of lamps was determined through manual on-site counting.

Table 10: Properties of luminaires

Type	Watt/per	Lumen	Number
Normal bulb	34	4500	1034
Spotlight1	35	4500	35
Spotlight2	35	4500	35

The thermal envelope properties are presented in Table 11. Information regarding the envelope layers was obtained from the architectural drawings available in the Malmö City Planning Office archive. The U-values were adopted from the ClimateStudio material library.

Table 11: Thermal transmittance (U-values) of the building envelope used in the energy simulation

	U-value ($W/m^2.K$)	Layer	Thickness (mm)
Exterior wall	0.31	200mm Concrete; 70mm insulation board; 20mm Timber; 20mm Mineral wool	310
Interior wall	3.50	13mm plaster; 13mm plaster	26
Roof	0.11	13mm Gypsum board; 20mm wood panels; 13mm Gypsum board; 250mm insulation board; 20 wood panels; 13mm gypsum board	329
Ceiling	0.35	50mm concrete sand; 50mm insulation board; waterproof paint; 18mm plywood; 100mm softwood; 6mm plywood	226
Ground	0.94	45mm wood wool board; 800mm concrete	845

3.8 Considerations regarding daylight distribution

In this study, attention is given not only to the quantity of daylight but also to its distribution within the exhibition space. Lighting in museums is typically composed of a combination of diffuse and directional light, which affects shadow formation and the visual perception of objects. While skylight systems can provide relatively uniform illumination across the space, they may result in lower illuminance levels on vertical surfaces where artworks are displayed. In addition, certain daylighting configurations can create high brightness levels at the ceiling, which may lead to visual discomfort or reflected glare. Therefore, evaluating both horizontal and vertical light distribution is essential for assessing the visual performance of museum spaces (Chaudhary, 2014).

4. Results

4.1 Daylight simulation

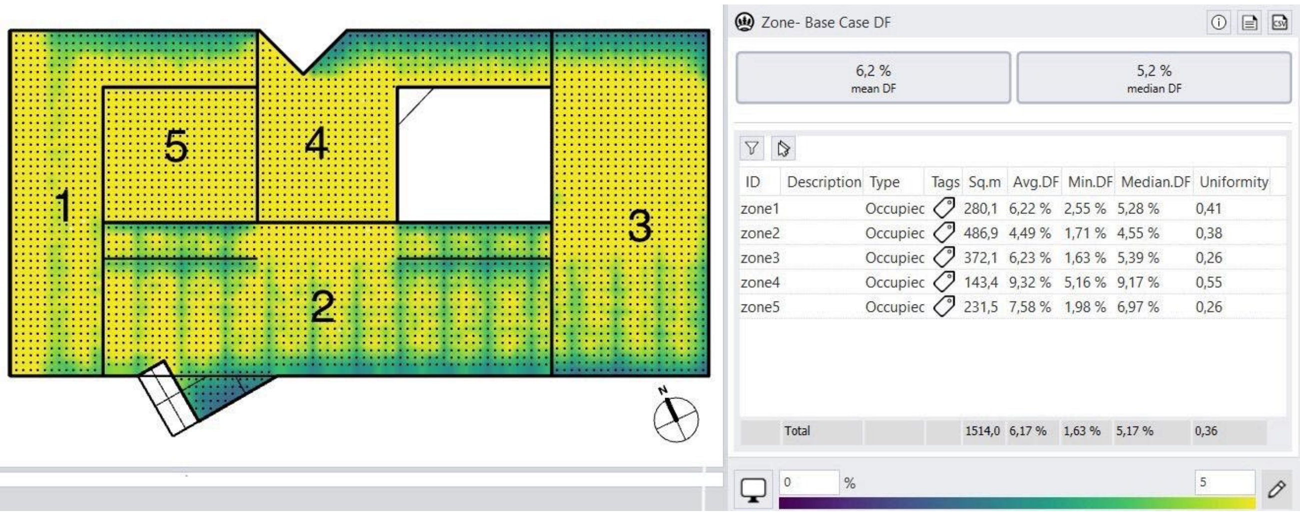
This section presents the results of the daylight simulations conducted in ClimateStudio. The analysis focuses on evaluating daylight performance in terms of availability, distribution, and visual comfort within the exhibition space.

4.1.1 Daylight Factor (DF)

The results of the Daylight Factor (DF) simulations are presented in Figure 16. The figure illustrates the zonal DF analysis of the exhibition space, which was divided into five sections to provide a more representative evaluation of daylight distribution. The results show a mean DF of 6.2% and a median DF of 5.2% for the overall analysed area. According to Tregenza and Wilson's classification, DF values between 2% and 5% generally correspond to well-daylit interiors, while values above 5% indicate a very bright environment where glare may become more likely (Tregenza & Wilson, 2011, as cited in Dubois et al., 2025). These results therefore indicate a high level of daylight availability within the exhibition space under overcast sky conditions.

The zonal analysis presented in Figure 15 shows that DF values vary across the exhibition space. Zone 4 recorded the highest average DF value (9.3%) and the highest uniformity (0.55), indicating strong and relatively even daylight distribution in this area. In contrast, Zone 2 showed the lowest average DF value (4.5%), while Zones 3 and 5 presented lower uniformity values (0.26), suggesting greater variation in daylight distribution. Lower DF values are generally observed near perimeter areas and in spaces partially obstructed by internal architectural elements, where daylight penetration is reduced.

The relatively high DF values can be explained by the building's daylighting strategy. The presence of skylights allows diffuse daylight to enter from above and spread across the interior, supporting a broad and diffuse distribution of light that is less dependent on façade orientation. These conditions provide good overall daylight availability, but they also indicate that illuminance levels may become excessive in certain areas. In exhibition spaces, this can be both beneficial and challenging, as sufficient daylight improves visibility while excessive illuminance may require careful control depending on the sensitivity of the artworks displayed.



6,2 %
mean DF

5,2 %
median DF

ID	Description	Type	Tags	Sq.m	Avg.DF	Min.DF	Median.DF	Uniformity
zone1		Occupiec		280,1	6,22 %	2,55 %	5,28 %	0,41
zone2		Occupiec		486,9	4,49 %	1,71 %	4,55 %	0,38
zone3		Occupiec		372,1	6,23 %	1,63 %	5,39 %	0,26
zone4		Occupiec		143,4	9,32 %	5,16 %	9,17 %	0,55
zone5		Occupiec		231,5	7,58 %	1,98 %	6,97 %	0,26
	Total			1514,0	6,17 %	1,63 %	5,17 %	0,36

Figure 16. Zonal Daylight Factor (DF) analysis for the base case exhibition space

4.1.1.1 Validation with measurements

To validate the simulation results, on-site photometric measurements were conducted under real operating conditions. The measured and simulated Daylight Factor (DF) values were compared along the same measurement line, as presented in Figure 17 and Figure 17. Figure 16 shows the measured DF values, while Figure 18 presents the corresponding simulated DF values along the selected line. The average measured DF was 8.9%, which was higher than the simulated values. The deviation between the measured and simulated average DF was 31.5%.

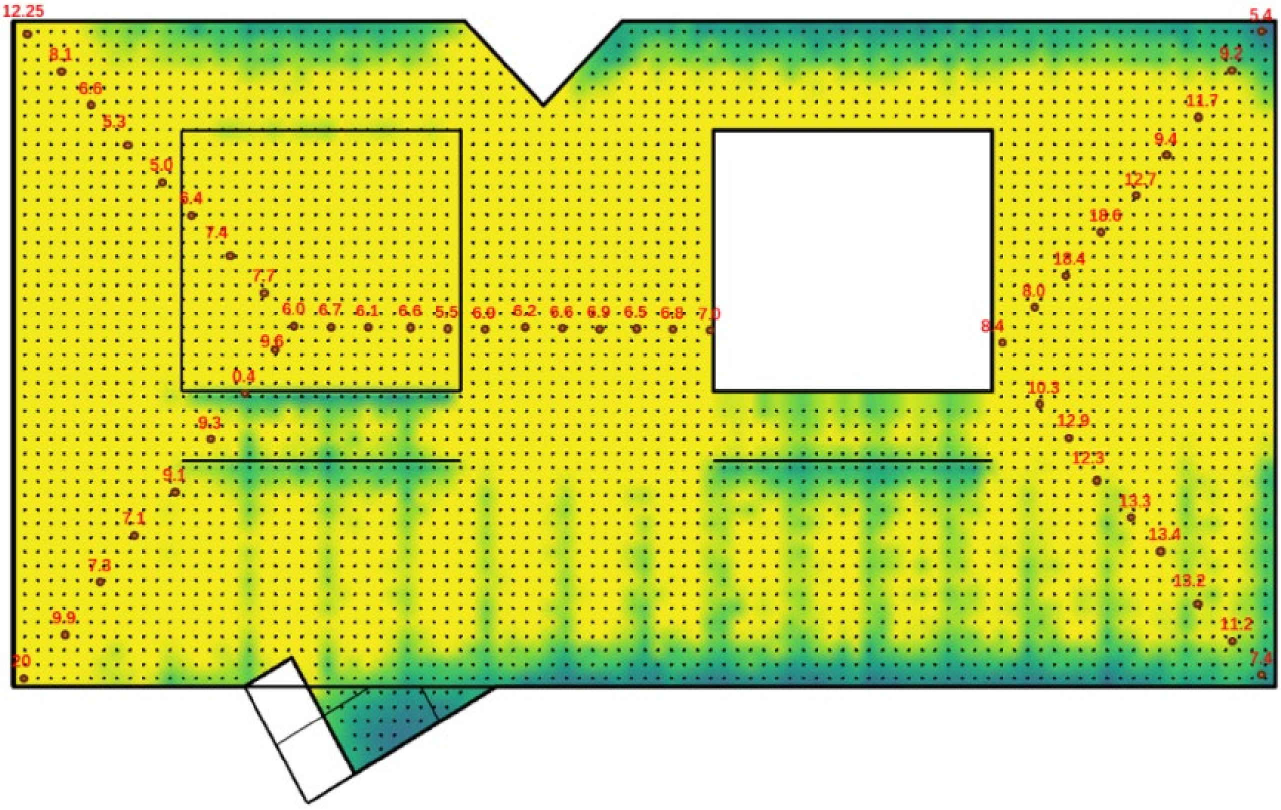


Figure 17. Measurement for DF in Konsthall (20/03/2026)

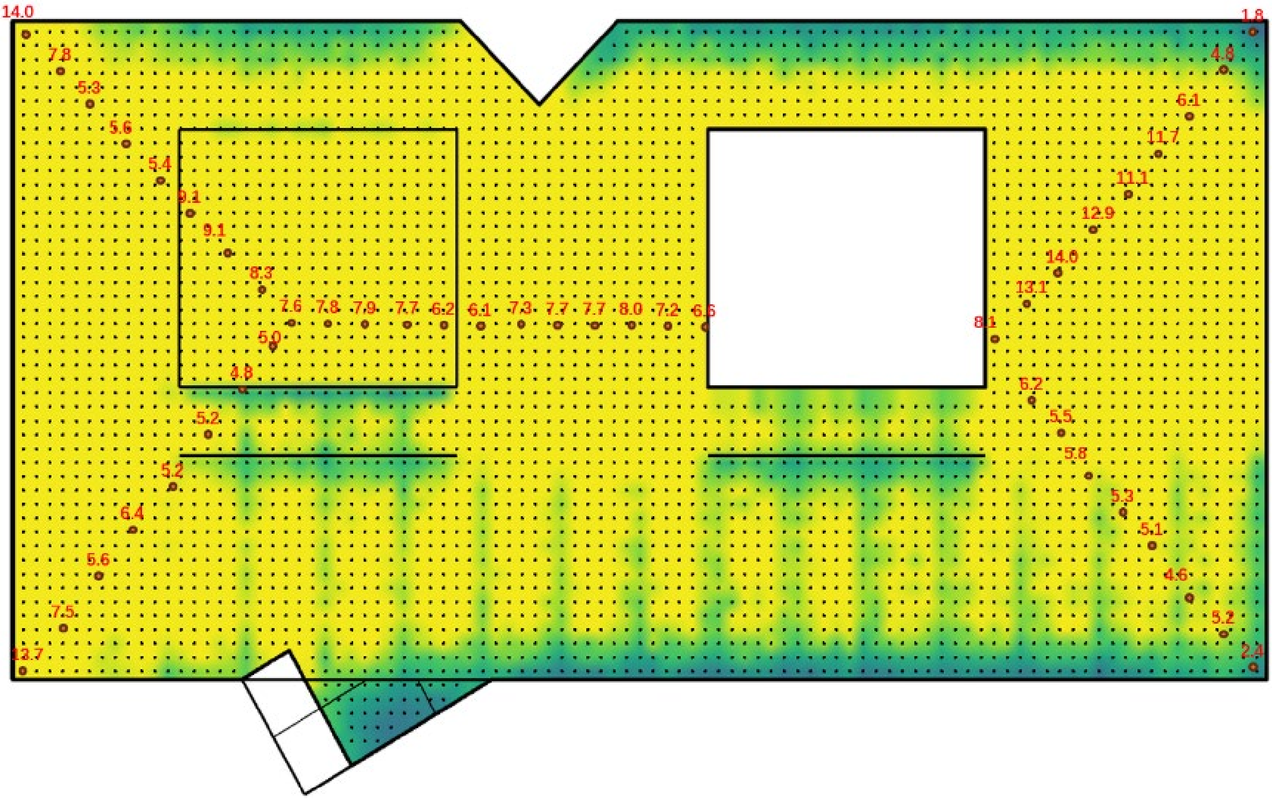


Figure 18. DF result in Konsthall by simulation (ClimateStudio)

The discrepancy between the measured and simulated Daylight Factor (DF) values can be explained by several factors. During the on-site measurements, the electric lighting system was operating. According to information provided by the museum technician, the exhibition space used ERCO lamps and standard LED light bulbs with a luminous flux of approximately 4500 lumen, and the lighting remained active during opening hours from 11:00 to 17:00. Based on these conditions, the electric lighting contribution was approximated at around 50 lux, which may have slightly increased the measured indoor illuminance levels compared to the daylight-only simulation results.

In addition, higher DF values were observed near the vertical glazing due to localized daylight penetration. Small variations in outdoor daylight conditions during the measurement period may also have contributed to the differences between the measured and simulated results. Moreover, approximately half of the primary skylight was shaded by the existing shading system during the measurements, which reduced the amount of daylight entering the space. In contrast, the simulation model assumed unshaded skylight conditions. This difference further contributed to the deviation between the measured and simulated DF values. Beyond these temporal factors, several systematic differences between the real environment and the simulation model may also explain the observed variation:

- Material properties: the reflectance and transmittance of real surfaces may differ from assumed values, particularly if surfaces are aged, soiled, or textured.
- Geometric accuracy: simplifications in the model geometry, such as frame thickness, can affect light distribution.
- Sky model assumptions: the simulation is based on a standard CIE overcast sky, which may not fully represent the actual sky luminance conditions during measurement.
- Sensor positioning: minor deviations in measurement point location or height may influence results. As measurements were conducted manually, a certain level of human error is unavoidable.

Overall, the DF results demonstrate strong daylight availability with a reasonably uniform distribution, while also highlighting the importance of considering real operating conditions when interpreting simulation results.

4.1.2 Glare

The glare analysis results are presented in Figure 19, while the fisheye luminance image is shown in Figure 20. Figure 18 indicates a generally low level of visual discomfort within the exhibition space. The results show that 2.4% of the analysed area experiences disturbing glare (sDG > 5% of occupied time) on an annual basis, meaning that glare affects only a limited part of the space for extended periods.

The glare distribution shown in Figure 19 indicates that these areas are mainly located near the west façade, where direct sunlight enters through the façade glazing. Most of the interior space remains within acceptable or imperceptible glare levels throughout the year. This is also visible in the fisheye luminance image presented in Figure 20, where high brightness values appear near the skylights and façade, while other areas remain relatively darker, creating visual contrast throughout the space.

The fisheye luminance image also illustrates the luminance distribution and luminance contrasts within the field of view. According to Dubois et al. (2025) luminance distribution and luminance contrast are important parameters in luminance-based assessments of visual comfort. Excessively high luminance contrasts may contribute to glare and visual fatigue, while excessively low contrasts may create a dull and non-stimulating visual environment. In this case, the observed luminance variation appears to remain within an acceptable range for most of the analysed area, which corresponds with the low percentage of disturbing glare presented in Figure 18. Moderate luminance variation may also contribute positively to spatial perception and visual interest within the exhibition space.

Overall, the results indicate that glare is generally controlled, although not fully eliminated. Some local areas still experience higher brightness levels and potential visual discomfort, particularly near the façade where daylight penetration is stronger.

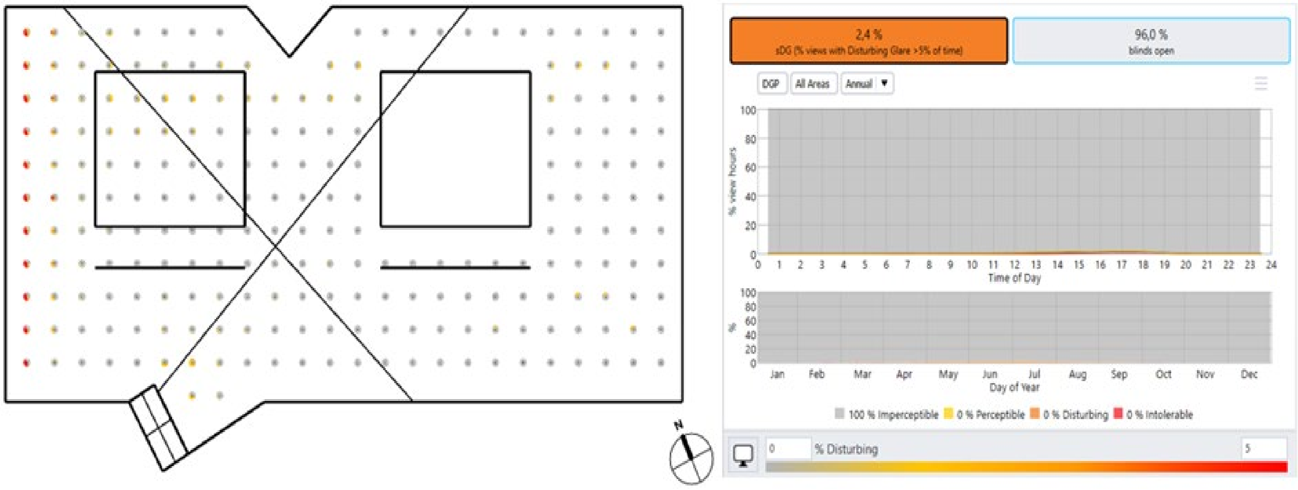


Figure 19. Spatial distribution of glare conditions across the exhibition space (left) and corresponding glare performance metrics (right)

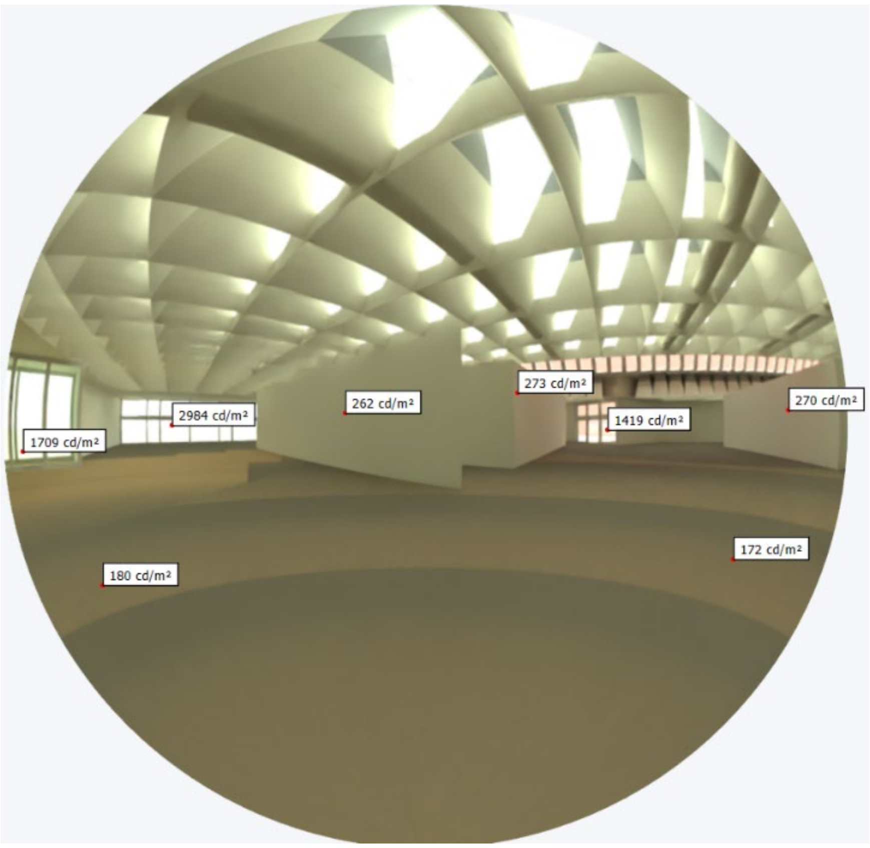


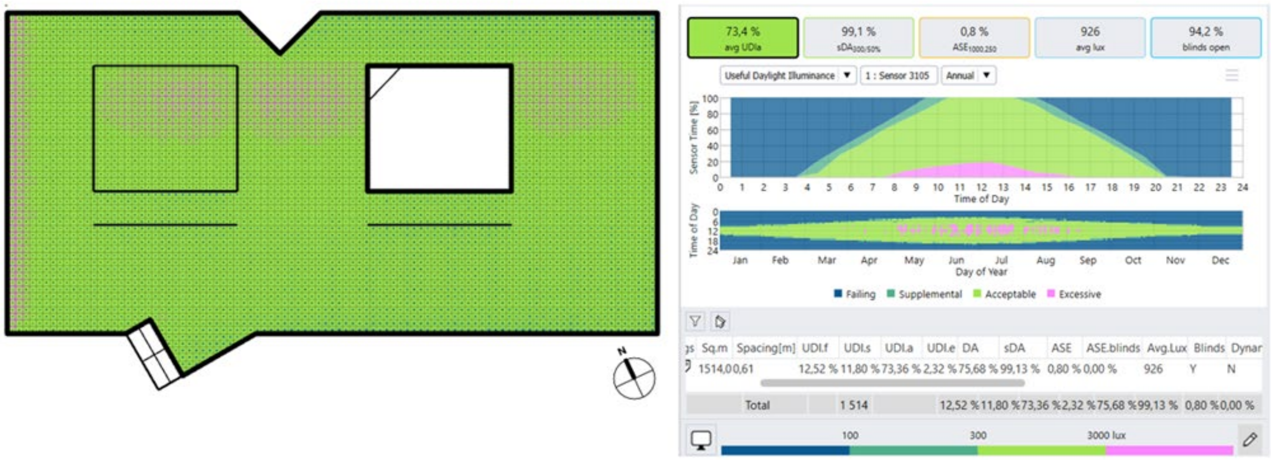
Figure 20. Fisheye rendering result for luminance, indicating point luminance values

4.1.3 Useful Daylight Illuminance (UDI)

The Useful Daylight Illuminance (UDI) results are presented in Figure 21. This figure shows that 73.4% of the analysed area falls within the useful illuminance range (100–3000 lux). This indicates that a large portion of the space receives daylight levels that are suitable for visual tasks during occupied hours. Only 12.5% of the area is underlit (below 100 lux), primarily located in zones further from daylight access or affected by internal partitions. Additionally, 11.8% of the area exceeds 3000 lux, indicating the presence of overlit zones where daylight levels are higher than 3000 lux.

The spatial distribution highlights that most of the space maintains illuminance within the useful range, while excessive light levels are concentrated near the west façade, where direct sunlight contributes to higher illuminance. Lower values are found in more enclosed or deeper areas of the plan. This pattern is clearly visible in the UDI distribution map, where most of the space appears within the acceptable range, with localized areas of underlit and overlit conditions.

These results indicate that, although daylight conditions are generally adequate, the occurrence of overlit zones reflects localized conditions where daylight intensity may be excessive. Overall, the UDI results demonstrate that most of the space achieves acceptable daylight levels, while also revealing areas where illuminance conditions fall outside the useful range.



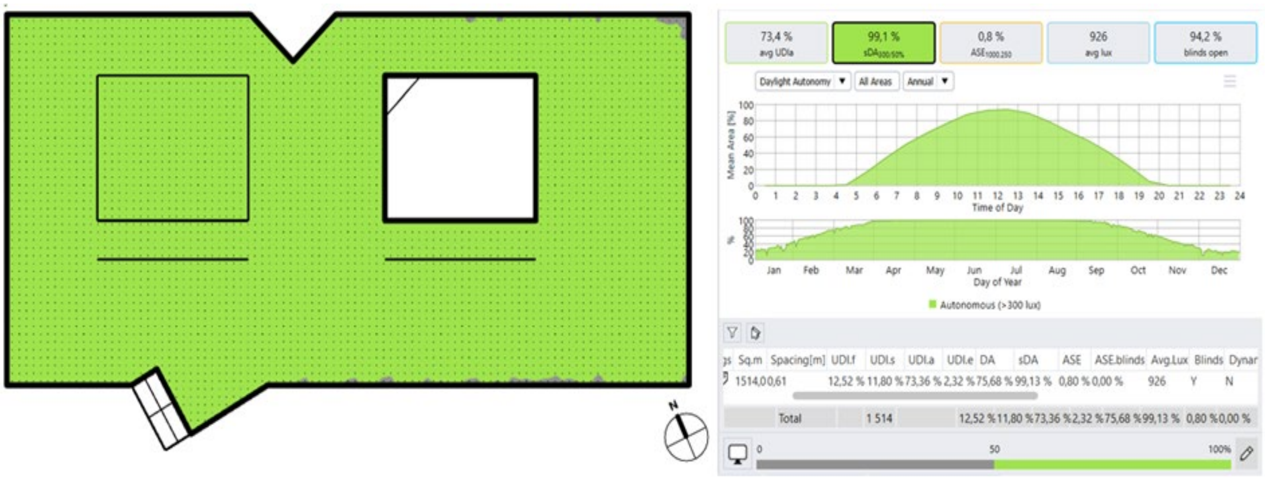
gs	Sq.m	Spacing[m]	UDI.f	UDI.s	UDI.a	UDI.e	DA	sDA	ASE	ASE.blinds	Avg.Lux	Blinds	Dynar
	1514,00	0,61	12,52 %	11,80 %	73,36 %	2,32 %	75,68 %	99,13 %	0,80 %	0,00 %	926	Y	N
Total	1 514		12,52 %	11,80 %	73,36 %	2,32 %	75,68 %	99,13 %	0,80 %	0,00 %			

Figure 21. Spatial distribution of UDI in the exhibition space (left) and corresponding daylight performance metrics (right)

4.1.4 Spatial Daylight Autonomy (sDA)

The results for the spatial daylight autonomy simulations are presented in Figure 22. This figure shows a very high level of spatial daylight autonomy, with a $\text{sDA}_{300\ \text{lux},\ 50\%}$ of about 99.1%. This means that almost the whole analysed area receives at least 300 lux for more than half of the occupied hours during the year. In this study, the occupied hours are defined as the museum opening time from 11:00 to 17:00, except Mondays. During these hours, most parts of the space have enough daylight.

The distribution also shows that nearly all areas meet the required daylight level, with only very small zones below the threshold. This means that daylight is uniformly distributed across the space. These results indicate that the building strongly relies on daylight as the main light source, and that electric lighting is almost redundant during daytime. Overall, the sDA results show that the space has very good daylight coverage, with most areas meeting the required performance level.



gs	Sq.m	Spacing[m]	UDI.f	UDI.s	UDI.a	UDI.e	DA	sDA	ASE	ASE.blinds	Avg.Lux	Blinds	Dynar
	1514,00	0,61	12,52 %	11,80 %	73,36 %	2,32 %	75,68 %	99,13 %	0,80 %	0,00 %	926	Y	N
Total	1 514		12,52 %	11,80 %	73,36 %	2,32 %	75,68 %	99,13 %	0,80 %	0,00 %			

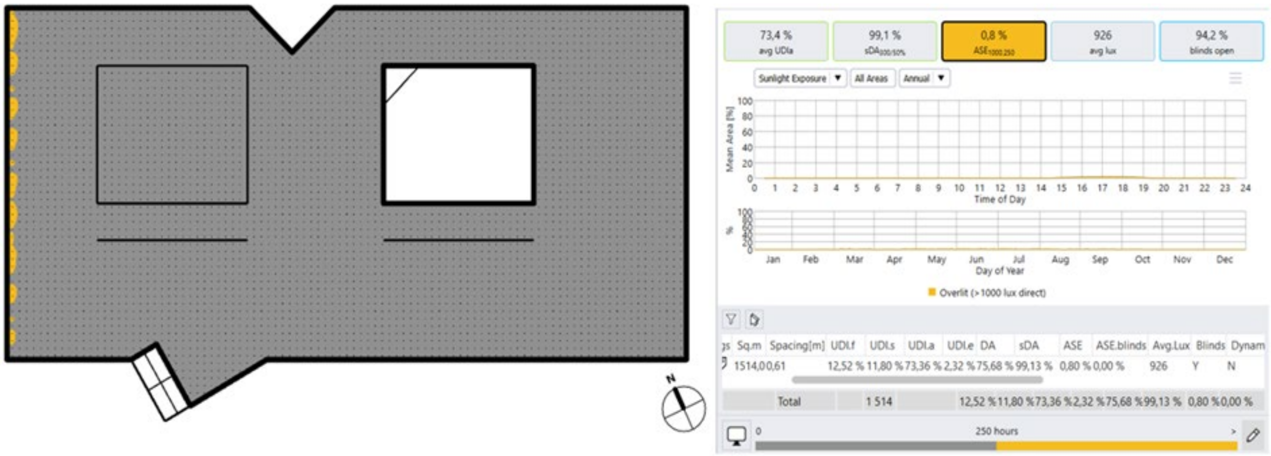
Figure 22. Spatial Daylight Autonomy (sDA) across the exhibition space (left) and corresponding daylight performance metrics (right)

4.1.5 Annual Sunlight Exposure (ASE)

The Annual Sunlight Exposure ($\text{ASE}_{1000,250}$) results are presented in Figure 23. This figure reveals a very low value of 0.8%, meaning that only a small part of the analysed area receives direct sunlight above 1000 lux for more than 250 hours per year.

The spatial distribution shows that areas with higher sunlight exposure are mainly concentrated along the west façade, where the space is exposed to direct sunlight during the late afternoon. In contrast, the majority of the exhibition space remains largely unaffected by direct sunlight, which shows that the cutoff angle for skylights (summer solstice) was calculated correctly by the architect. This pattern is clearly visible in the ASE distribution map, where exposure is limited to narrow zones near the façade.

These results reflect the influence of building orientation and daylighting strategy. While the west façade allows localized direct sunlight penetration, the dominant source of daylight is provided by the roof skylights, which primarily introduce diffuse light into the interior. As a result, direct sunlight remains confined to perimeter zones and does not extend into the deeper areas of the plan.



Sq.m	Spacing[m]	UDI.f	UDI.s	UDI.a	UDI.e	DA	sDA	ASE	ASE.blinds	Avg.Lux	Blinds	Dynam
1514,00	0,61	12,52 %	11,80 %	73,36 %	2,32 %	75,68 %	99,13 %	0,80 %	0,00 %	926	Y	N
Total 1 514		12,52 %	11,80 %	73,36 %	2,32 %	75,68 %	99,13 %	0,80 %	0,00 %			

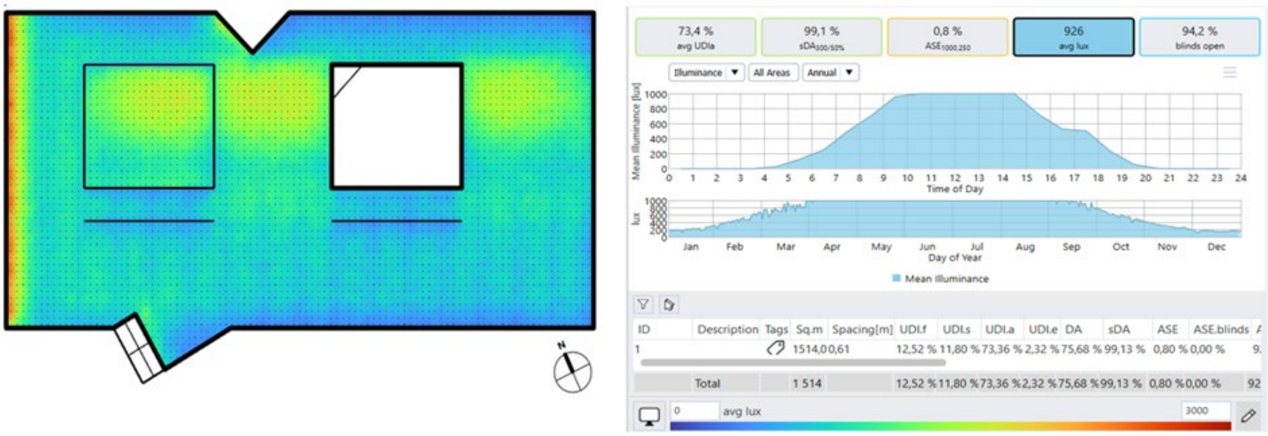
Figure 23. Spatial distribution of Annual Sunlight Exposure (ASE) across the exhibition space (left) and corresponding performance metrics (right)

4.1.6 Average Illuminance (lux)

The results for average illuminance simulations are shown in Figure 24. This figure indicates an average illuminance of approximately 926 lux across the analysed area. This value expresses the average daylight conditions over the year during the defined occupied hours (11:00–17:00, excluding Mondays), indicating relatively high daylight levels throughout the space.

The distribution of illuminance is not uniform. Higher values are concentrated along the west façade, where direct sunlight contributes to increased light intensity, particularly during the afternoon. In contrast, lower illuminance levels are found in areas located further from this façade and in zones affected by internal elements.

Although daylight reaches a large portion of the interior, the average illuminance level exceeds typical recommendations for exhibition environments. According to established guidelines, acceptable illuminance levels depend on the sensitivity of the exhibited materials. Highly sensitive objects, such as photographs, paper, textiles, and watercolors, should be exposed to around 50 lux, while materials with medium sensitivity can tolerate up to 200 lux. Less sensitive materials may be exposed to levels up to 300 lux (Museums Galleries Scotland, 2024). The presence of localized high illuminance zones suggests that certain areas may be exposed to excessive light levels. These results indicate that while daylight availability is sufficient, careful control of light intensity may be necessary to ensure appropriate conditions for the display and preservation of artworks.



ID	Description	Tags	Sq.m	Spacing[m]	UDI.f	UDI.s	UDI.a	UDI.e	DA	sDA	ASE	ASE.blinds	A
1			1514,0	0,61	12,52 %	11,80 %	73,36 %	2,32 %	75,68 %	99,13 %	0,80 %	0,00 %	9.
	Total		1 514		12,52 %	11,80 %	73,36 %	2,32 %	75,68 %	99,13 %	0,80 %	0,00 %	92

Figure 24. Spatial distribution of average illuminance (lux) across the exhibition space (left) and corresponding annual illuminance metrics (right)

It should be noted that the DF is evaluated under CIE overcast sky conditions, while the other metrics are based on annual climate-based simulations, which are rooted from climate data. The summary of daylight simulation results are presented in Table 12.

Table 12: Summary of daylight simulation results and performance indicators for the exhibition space

Metric	**Result**	**Interpretation**
Mean Daylight Factor (DF, %)	6.2	High daylight availability under standard overcast sky conditions
Median Daylight Factor (DF, %)	5.2	
Glare (sDGP > 5%, %)	2.4	Low glare risk
Useful Daylight Illuminance (UDI300–3000, %)	73.4	Majority of the space receives useful daylight, with some overlit zones near the façade
Spatial Daylight Autonomy (sDA300/50, %)	99.1	Excellent daylight sufficiency across the space, complete daylight autonomy.
Annual Sunlight Exposure (ASE1000,250, %)	0.8	Very low risk of excessive direct sunlight exposure
Average Illuminance (lux)	926.0	Relatively high daylight levels across the space during occupied hours

4.2 Annual average illuminance on artworks

This section presents the analysis of annual average illuminance on selected artworks within the exhibition space.The evaluation focuses on the light exposure at these specific positions to assess potential risks related to excessive illuminance and to compare the results with recommended conservation limits.

The results show that the annual average illuminance levels on artworks vary across the exhibition space (Figure 24), based on climate-based simulations during the defined occupied hours.

In general, illuminance levels range approximately from 190 lux to around 960 lux, depending on the location of the artworks. Lower values are observed in more enclosed areas (e.g., Artworks 2 and 4, around 190–320 lux), while higher values occur in areas more exposed to daylight (e.g., Artworks 3, 7 and 9, reaching up to 610–966 lux).

Most artworks (e.g., Artworks 1, 5, 6, and 8) have illuminance within a range of approximately 300–500 lux. However, several artworks are exposed to over 700 lux, indicating strong daylight penetration in certain zones, especially near skylights or glazed façades (see Figures 25–28).

The analysed artworks are generally considered to have medium to low sensitivity to light, with recommended illuminance levels typically between 200 lux and 300 lux. Based on these thresholds, some artworks fall close to acceptable levels, while others are exposed to significantly higher illuminance than recommended, with a risk of damaging the artwork. It should also be noted that highly light-sensitive artworks are displayed in enclosed rooms without daylight access and are therefore not included in this analysis.

Overall, the results indicate that while daylight provides good visibility within the exhibition space, illuminance levels are not consistently controlled and exceed recommended limits in several areas, particularly near daylight openings.

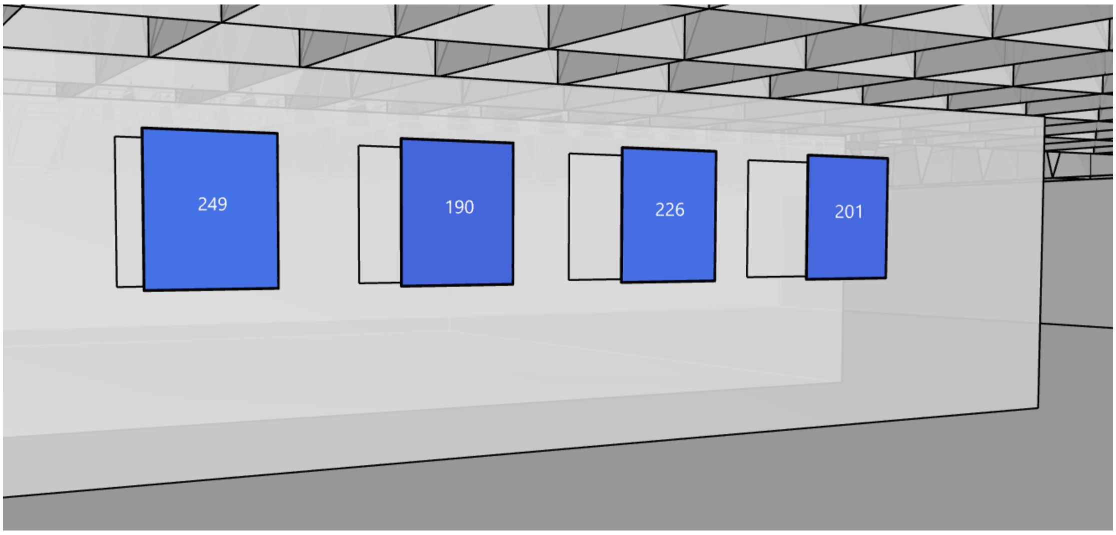


Figure 25. Average annual illuminance (lux) on artworks 2 within the exhibition space

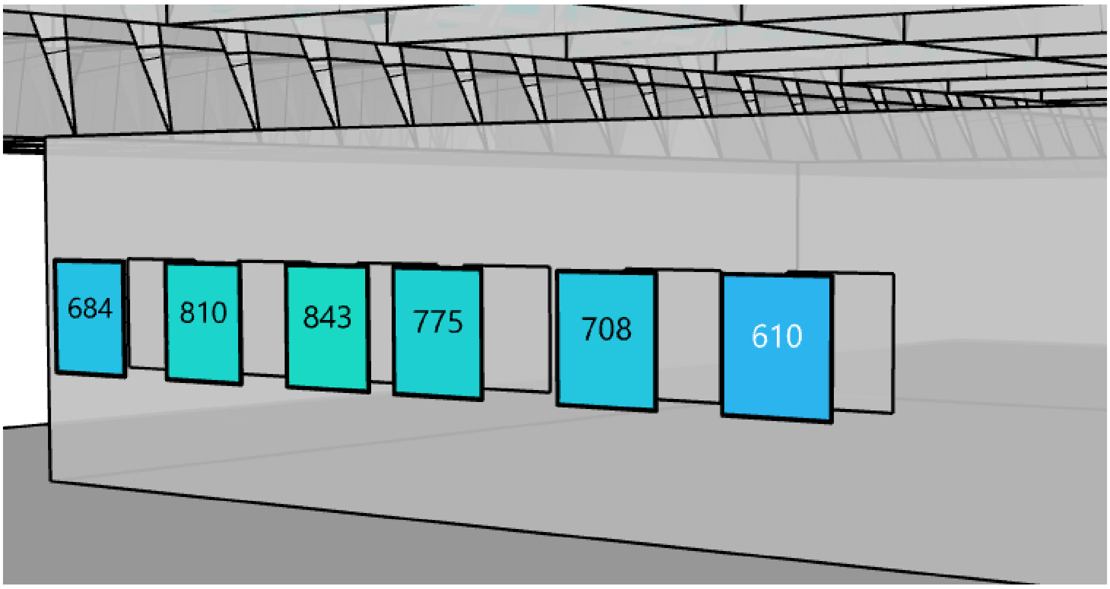


Figure 26. Average annual illuminance (lux) on artworks 3 within the exhibition space

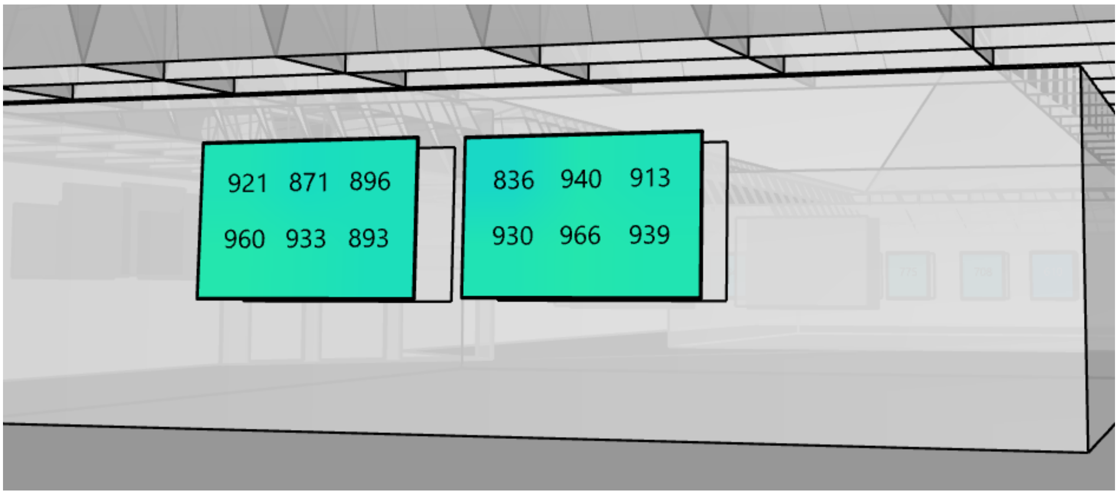


Figure 27. Average annual illuminance (lux) on artworks 7 within the exhibition space

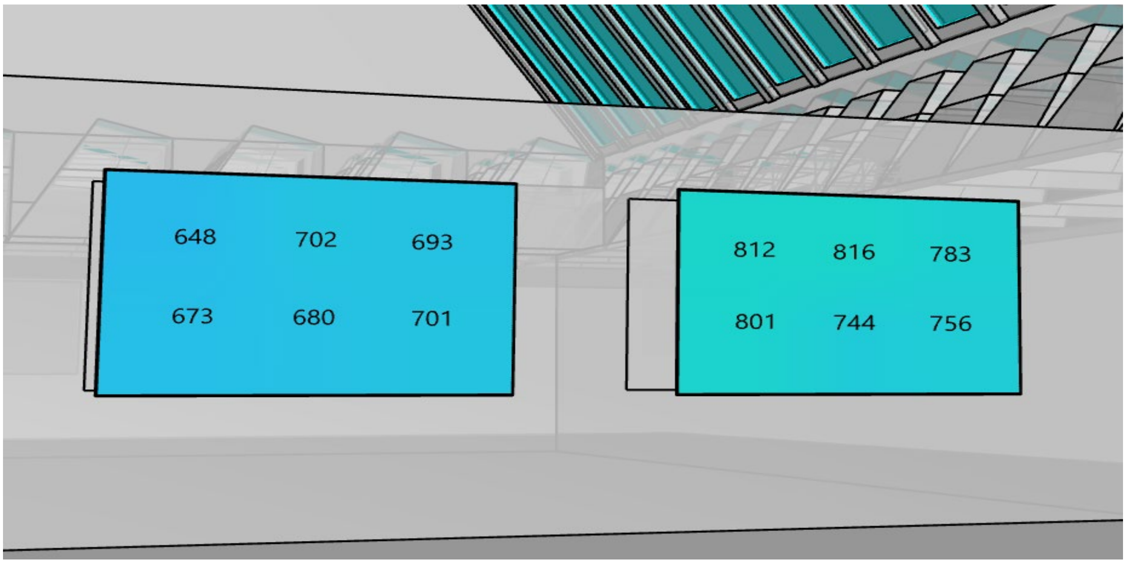


Figure 28. Average annual illuminance (lux) on artworks 9 within the exhibition space

4.3 Energy simulations

Figure 29 shows that the annual energy simulation results in Grasshopper indicate that the simulated building has a total energy use intensity (EUI) of 188.6 kWh/m²yr and total annual energy use is 315833 kWh for exhibition space. This EUI value exceeds the building code requirement, which sets a maximum limit of 70 kWh/m²yr. Compared to the energy declaration from Malmö Stad, Stadsfastigheter, which is 205 kWh/m2yr, the simulation results show a deviation of approximately 10% from the actual energy use, which is acceptable.

Approximately 71.3% of the total load is for heating, which accounts for 134.4 kWh/m²yr. This is followed by electric lighting load at 41.3 kWh/m²yr, which represents 21.9% of the total energy demand.

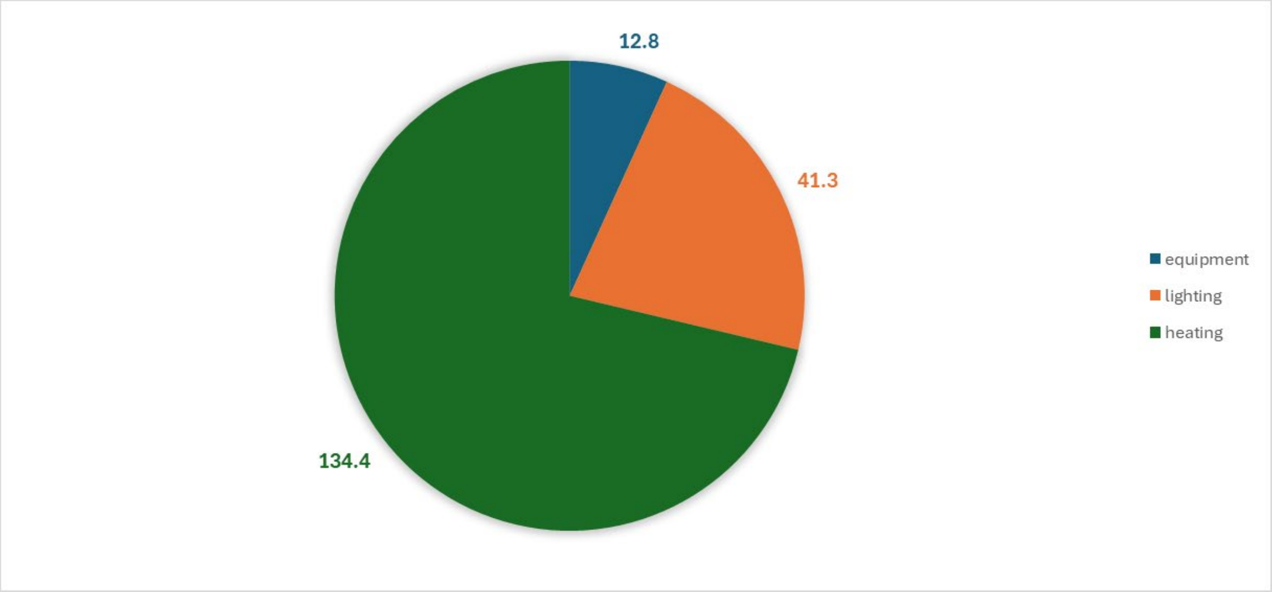


Figure 29. Annual energy use distribution (kWh/m²yr)

The monthly distribution of energy use is presented in Figure 30. The heating energy demand exhibits pronounced seasonal variation, whereas the equipment and lighting loads remain relatively constant throughout the year. The highest heating demand occurs in January, reaching 21.6 kWh/m²; it gradually decreases to 0 kWh/m² in July. This pattern reflects the typical heating profile of buildings located in northern climates, where winter conditions drive substantial heating requirements.

In contrast, the lighting and equipment loads show minimal fluctuation across the year, with average values of 2.9 kWh/m²yr and 0.9 kWh/m²yr, respectively. These loads are primarily determined by the operation schedule, which is applied uniformly throughout the year, resulting in constant energy use regardless of seasonal changes.

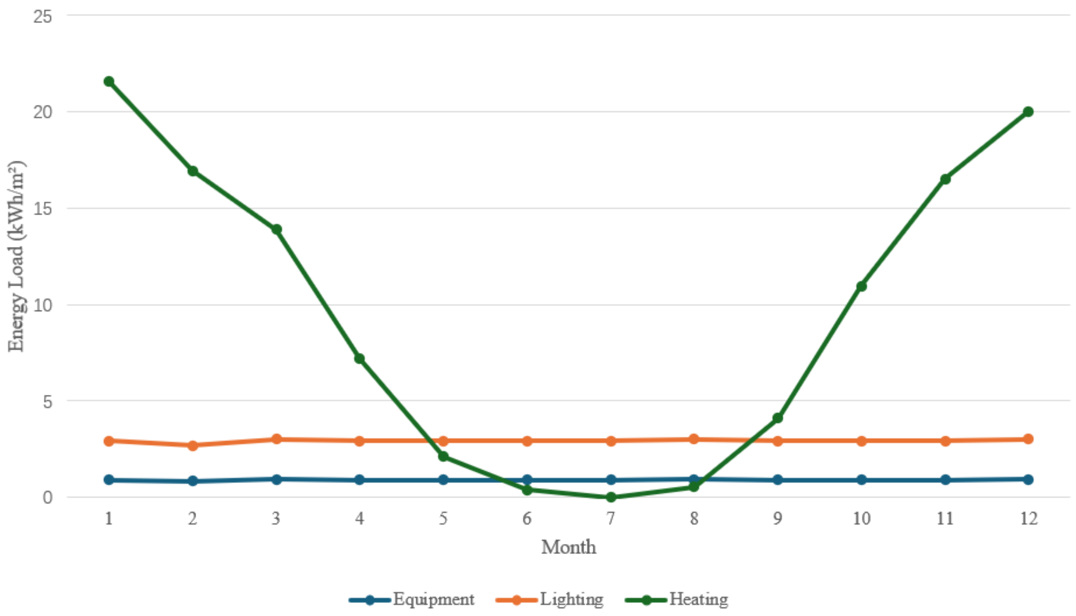


Figure 30. Monthly energy load profiles for the Malmö Konsthall (kWh/m²), simulated via ClimateStudio

The results also indicate a seasonal shift in the dominant energy load. From September to May, the heating energy demand represents the largest share of total energy use, reflecting the increased demand during colder months. In contrast, during the summer period (May to September), the heating demand drops significantly, and the lighting load becomes the primary contributor to total energy uses. This seasonal transition aligns with the reduced need for heating and the consistent operational schedule of the lighting system.

A comparison between the LENI-based calculation and the simulation results is presented in Table 13. A notable discrepancy is observed: the annual lighting load estimated using the LENI method is 35.5% lower than the value obtained from the simulations. This difference highlights the sensitivity of lighting energy estimates to the underlying assumptions and calculation methods.

Table 13: Lighting load from LENI calculation and Software simulation

	LENI (kWh/m²)	**Simulation (kWh/m²)**
Lighting load	26.6	41.3

The difference between these two results can be explained by the LENI calculation, which includes some factors such as daylight dependency and occupancy dependency (Nulty, 2013). In contrast, the simulation results present the maximum potential energy uses under the condition that lighting fixtures are on full power.

4.4 Survey

A survey based on the Belupp method (see Appendix A) was conducted at the beginning of this study to better understand how the exhibition space is perceived by visitors. For this, a total of ten valid questionnaires were distributed and collected. Two staff members and eight visitors answered the survey. They were aged between 25 and 40 years. While the sample size is limited, it provides an initial indication of how lighting conditions are perceived within the exhibition space. The survey results are summarized in Table 14.

Table 14: Results from the questionnaires

	Hedonic tone	Brightness	Variation	Colour	Flicker
Mean	4.9	5.0	3.6	3.2	2.0

The hedonic tone received an average rating of 4.9, which is clearly above the midpoint of the scale (1-7 where 1 is negative and 7 is positive). This suggests that the lighting conditions evoke a generally pleasant emotional response among visitors. The brightness rating of 5 further indicates that the space is perceived as bright, aligning with the results from Table 14, where participants also tended to describe the environment as bright rather than dark.

The variation score of 3.6 suggests that the luminous environment is perceived as relatively uniform. This contributes to a calm and visually comfortable atmosphere, which is desirable in exhibition spaces. The colour rating of 3.2 indicates a tendency toward cooler tones. This aligns with museum lighting practices, where cooler light improves visual clarity and colour rendering.

Finally, the flicker rating of 2 is notably low, indicating that visitors perceived very little flicker in the lighting system. This is an important factor for visual comfort, as flicker can cause fatigue or discomfort in sensitive individuals. The space is also dominated by daylight, which is intrinsically flicker-free so this result was expected.

The results from Table 15 show that the lighting environment is perceived as bright, comfortable, stable, and visually supportive. These findings align with the attribute-based responses in Table 15 and confirm that the lighting conditions in Konsthall are generally favourable, with light that is evenly distributed, soft, and largely flicker-free.

Table 15: Details results from the questionnaires

Attribute	Mean rating (1-7)	Most selected perception
Dark - Light	5.5	Light
Pleasant - Unpleasant	2.5	Pleasant
Uncoloured -Coloured	3.2	Moderately cool
Strong - Weak	3.5	Moderately strong
Scattered - Concentrated	5.3	Concentrated
Warm - Cool	4.0	Neutral
Uneven distributed – Even distributed	5.8	Even distributed
Hard-Soft	6.5	Soft
Unfocused - Focused	5.8	Focused
Natural - Unnatural	3.8	Neutral
Flicker – No flicker	6.0	No flicker
Clear - Drab	3.0	Clear
Varied - Monotonous	4.0	Neutral
Mild - Sharp	4.0	Neutral
Glaring - Shaded	3.8	Neutral
Subdued - Brilliant	5.0	Brilliant

Regarding the overall assessment of lighting conditions, most participants provided positive feedback, indicating that the lighting environment in Konsthall was perceived as favorable.

5. Parametric study

The parametric study was conducted to investigate potential design strategies for improving daylight and energy performance in Malmö Konsthall. The improvement measures were identified based on the results of the base case analysis. For daylight performance, the main challenges were excessive illuminance levels on artworks. Therefore, two daylight-control strategies were investigated: partial skylight blocking and façade glazing modification. These measures were selected because they directly affect daylight penetration into the exhibition space.

For energy performance, a number of building envelope and lighting improvements were evaluated individually to assess their impact on heating demand and overall energy performance. The results of these analyses were subsequently used to develop and evaluate the final improved case.

5.1 Improvement of annual average illuminance on artworks

Although the daylight simulation results indicated adequate daylight availability, the annual average illuminance levels on artworks remained relatively high in several areas. This is a critical issue in museum environments, where excessive illumination can negatively affect the preservation of artworks. Therefore, a parametric study was conducted to reduce illuminance levels while maintaining acceptable daylight conditions.

The implemented improvement strategy consisted of two main modifications. First, half of the lower portion of the skylight was blocked to reduce the amount of direct daylight entering the exhibition space. This intervention aimed to decrease excessive illumination while also contributing to reduce the heating demand, which was high according to the first simulation. Secondly, the glazing type of the wall facade and exterior glazed was changed. A similar daylight control approach has been applied in the Musée national des beaux-arts du Québec, where glazing systems are used to control daylight penetration and support the conservation of artworks (OMA, n.d.). The original glazing was Solarban 60 clear argon triple glazing with a visible light transmittance (VLT) of 55% (Figure 14). In the improved case, this was replaced with Kalwall 100 mm, WhiteWhite, TVIS 5%, which has a much lower light transmittance (Figure 31), but less heat losses due to a lower U-value (0.45 W/m^2.K). This change was made to reduce strong daylight penetration from the glazed façade while reducing the heating load.

Layers: (Outside - Inside)

1 - White 2 [mm]
2 - RAH 13 [mm]
3 - DRAH 70 [mm]
4 - RAH 13 [mm]
5 - White 1 [mm]

Kalwall 100mm Opt_2 WhiteWhite Tvis 5%

VLT	5 %
VLR	40 % / 40 %
UVal	0,45
SHGC	0,04

Figure 31. Kalwall properties in ClimateStudio

The results show that these modifications reduced the annual average illuminance levels on most artworks in the exhibition space (Figure 32-35). In Set 1, the values were reduced to 355-455 lux (≈ 20% reduction). In Set 2, the values were around 189-211 lux (≈ 24% reduction), which is close to recommended museum illuminance levels. In Set 3, the values ranged from 301 to 392 lux (≈ 57% reduction), while Set 4 reached 264 lux (≈ 18% reduction). In Set 5, the illuminance levels were further reduced to approximately 237-287 lux (≈ 37.5% reduction), and in Set 6 the values were around 317-376 lux (≈ 28% reduction).

A clear improvement was also observed in Set 7, where the values were reduced to 204-261 lux (≈ 74% reduction). This is an important result, since this area was previously one of the most exposed zones. In Set 8, the values ranged from 217 to 321 lux (≈ 19% reduction), and in Set 9, the illuminance levels were reduced to 301-380 lux (≈ 56% reduction).

Diffuse glazing in the Kalwall system contributed to reducing intense light and glare and created more even lighting conditions in the exhibition spaces, although it also reduced the visual connection to the outside. However, it offers an additional advantage, as the façade can still function as a light source during evening hours while contributing to reducing the heating demand. In this study, changing the façade glazing also helped improve the daylight conditions in the exhibition area.

Overall, the improved case shows that the combined strategy was effective in lowering illuminance on the artwork and creating more controlled daylight conditions in the exhibition space. The reduction was especially important in areas that previously received stronger daylight. Some artworks still remained slightly above the preferred range, which means that the strategy significantly improved the conditions, but did not fully eliminate high illuminance in all locations.

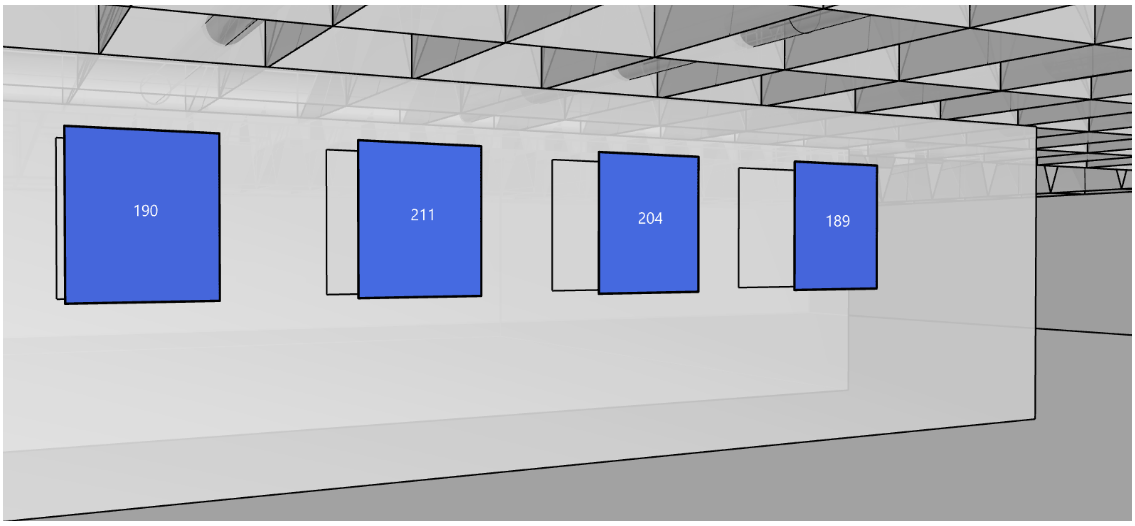


Figure 32. Improvement of Average Illuminance on Artworks – Set 2

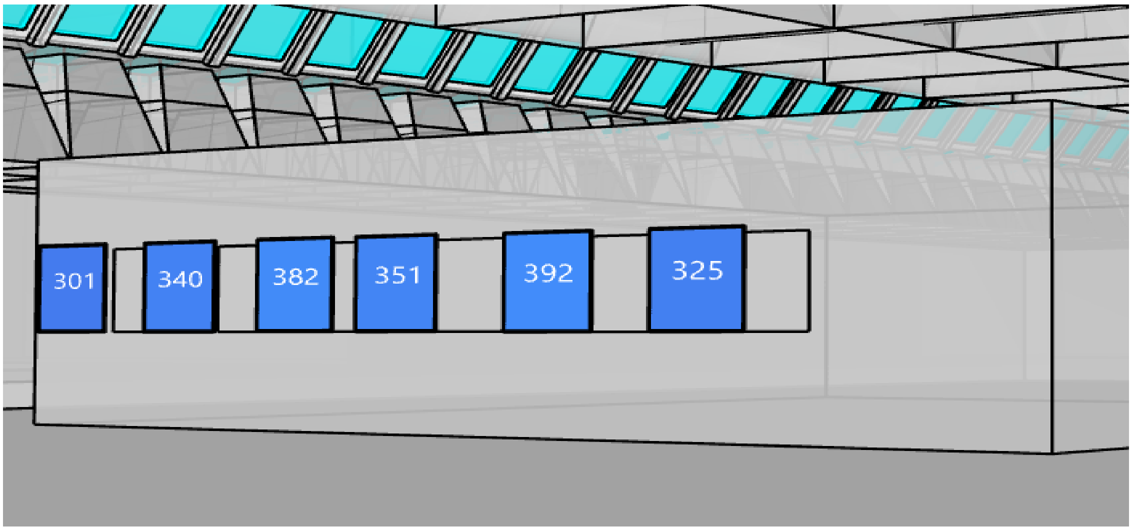


Figure 33. Improvement of Average Illuminance on Artworks – Set 3

Figure 34. Improvement of Average Illuminance on Artworks – Set 7

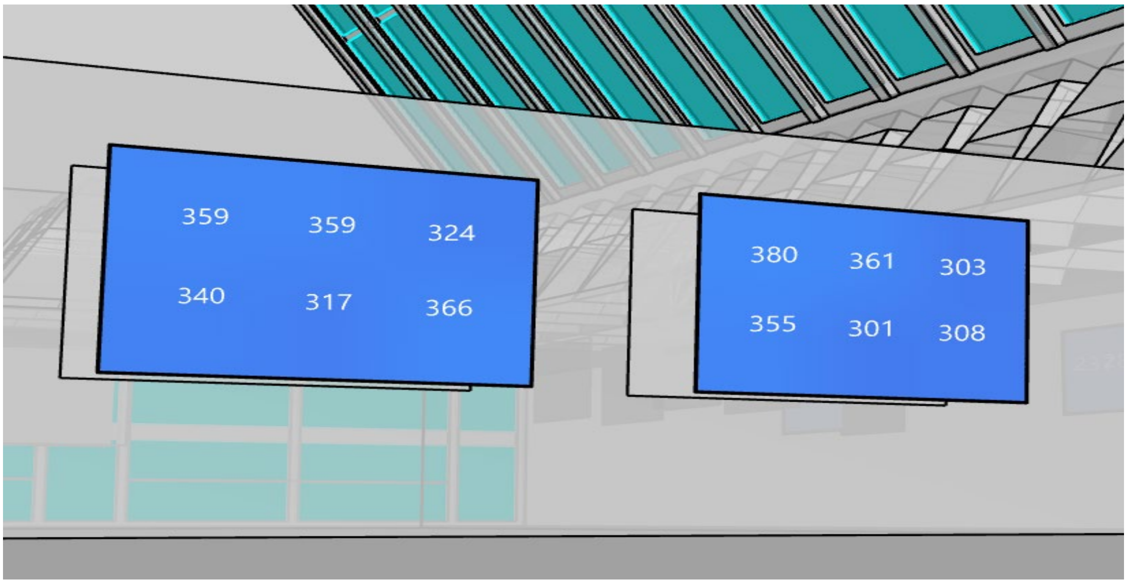


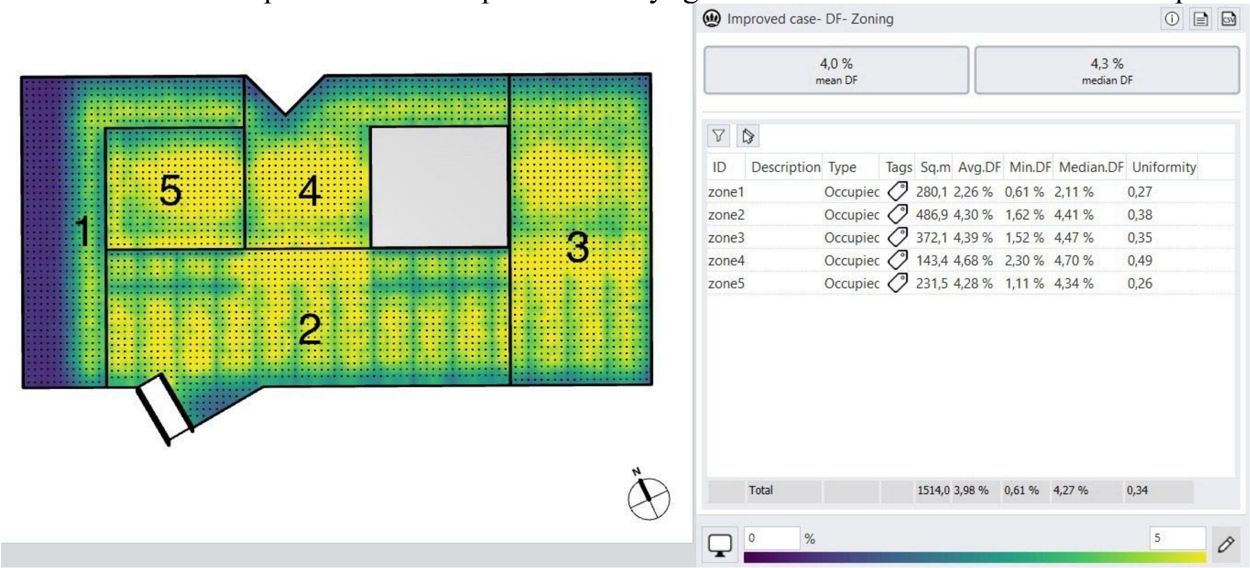
Figure 35. Improvement of Average Illuminance on Artworks – Set 9

5.2 Effect of improvements on exhibition area

Although the implemented strategies were mainly intended to reduce the illuminance levels on artworks, the results show that these modifications also influenced the overall daylight performance of the exhibition area.

The Daylight Factor (DF) results for the improved case show a mean value of 4.0% and a median value of 4.3% (Figure 36), indicating good daylight availability. To better represent the spatial variation in the large exhibition area, the uniformity was evaluated using a zonal approach, dividing the space into five sections. The results show that uniformity varies between 0.3 and 0.5, with higher values in central areas and lower values near façade openings and skylights. The overall uniformity for the space is 0.3, which is higher than in the base case, but still too low with respect to requirements of 0.4 for informal spaces (see EN 12464).

Applying the same zonal evaluation method to both the base case and the improved case enables a more consistent and representative comparison of daylight distribution within the exhibition space.



4,0 %
mean DF

4,3 %
median DF

ID	Description	Type	Tags	Sq.m	Avg.DF	Min.DF	Median.DF	Uniformity
zone1		Occupiec		280,1	2,26 %	0,61 %	2,11 %	0,27
zone2		Occupiec		486,9	4,30 %	1,62 %	4,41 %	0,38
zone3		Occupiec		372,1	4,39 %	1,52 %	4,47 %	0,35
zone4		Occupiec		143,4	4,68 %	2,30 %	4,70 %	0,49
zone5		Occupiec		231,5	4,28 %	1,11 %	4,34 %	0,26
	Total			1514,0	3,98 %	0,61 %	4,27 %	0,34

Figure 36. Zonal Daylight Factor (DF) simulation results for the improved case exhibition space

The glare analysis results for the improved case are presented in Figure 37, while Figure 38 compares the fisheye luminance images of the base case and the improved case. The results indicate that the implemented daylight improvement strategies significantly reduced visual discomfort within the exhibition space. In the improved case, no disturbing glare was recorded within the analysed area (0% sDG > 5% of occupied time), indicating that direct sunlight no longer causes significant visual discomfort for visitors.

Figure 38 shows that the improved case has a more balanced luminance distribution within the field of view compared to the base case. In the base case, high luminance values were concentrated near the façade glazing and skylight areas, creating strong visual contrasts between bright and darker surfaces. After the implemented improvements, these luminance contrasts were visibly reduced, resulting in smoother transitions between bright and dark areas throughout the exhibition space.

Although some luminance variation remains visible near the skylights and façade openings, the improved case shows reduced luminance contrasts and a more balanced luminance distribution compared to the base case. The implemented improvements reduced the contrast between high-brightness and darker areas within the field of view, resulting in smoother luminance transitions throughout the exhibition space. However, complete luminance uniformity is not desirable in exhibition environments either (Dubois et al., 2025), as it may create a visually monotonous environment devoid of shadows or directionality. The results therefore indicate that the implemented strategies created more controlled and visually comfortable daylight conditions while still maintaining spatial perception and visual interest within the exhibition space.

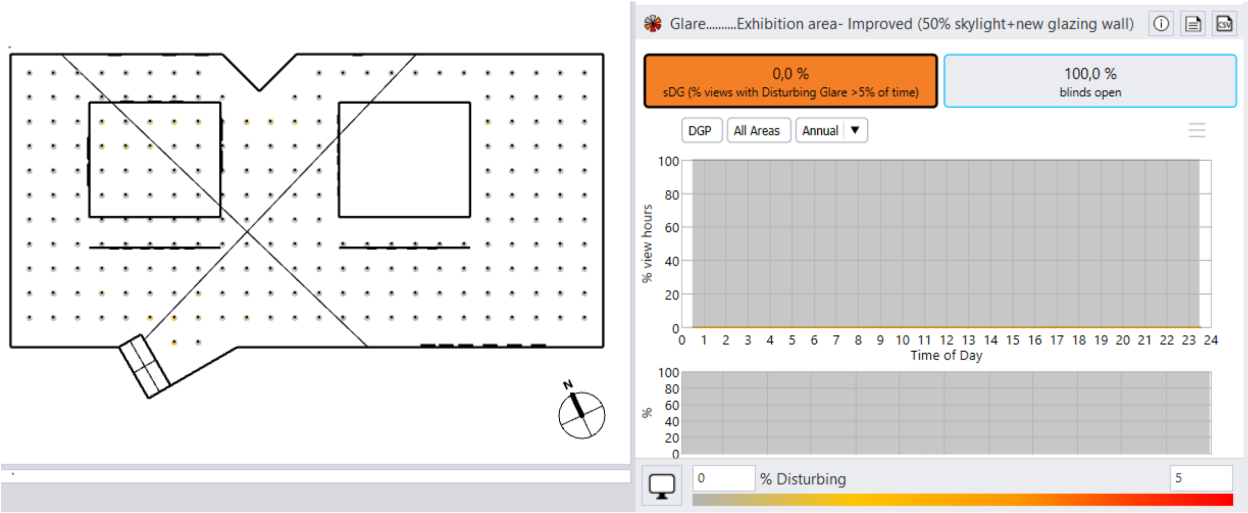


Figure 37. Glare analysis (sDG) in the exhibition area after improvement

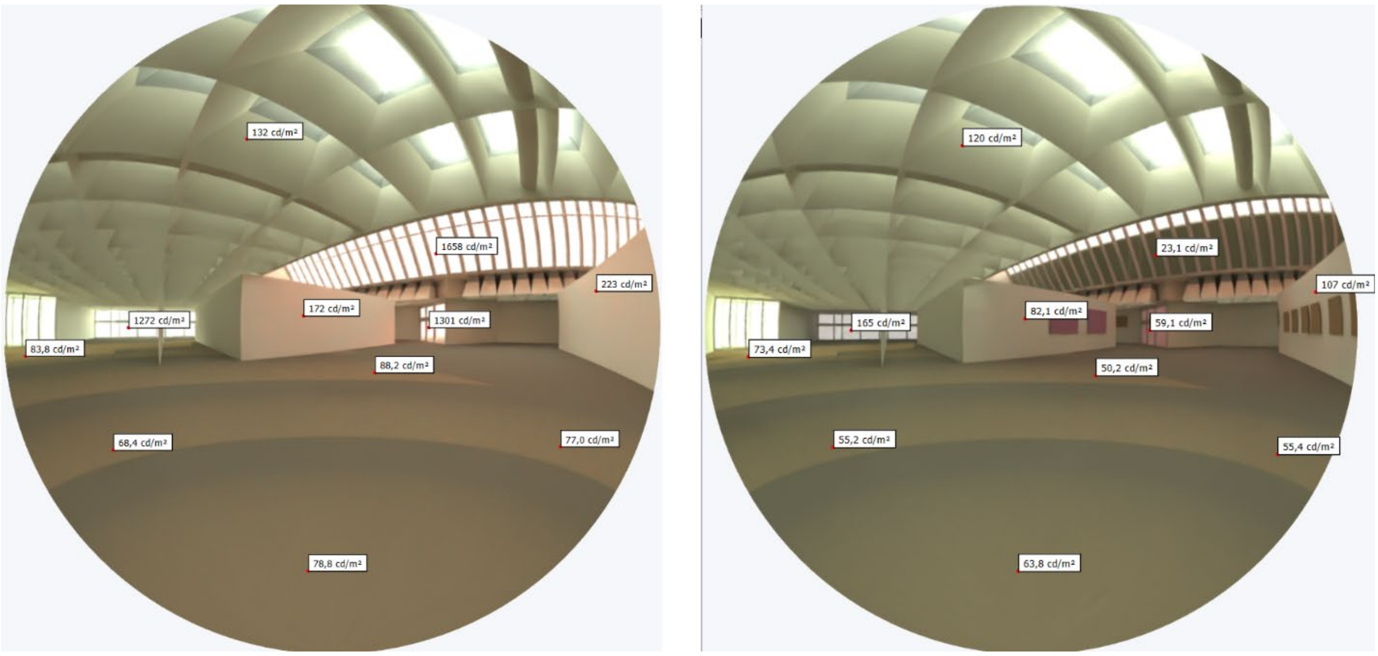
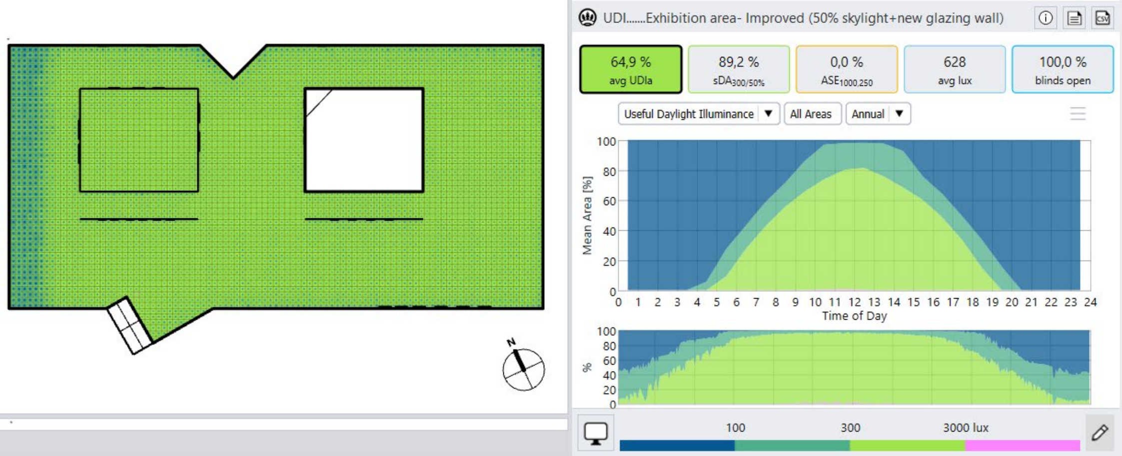


Figure 38. Comparison of fisheye luminance images for the base case (left) and improved case (right), illustrating the effect of the implemented daylight improvements on luminance distribution, luminance contrast, and visual comfort within the exhibition space

Figure 39 shows that the UDI reached 64.9% (Figure 39), indicating that a large portion of the space still falls within the useful illuminance range (100–3000 lux). Compared to the base case (73.4%), this represents a decrease in UDI. However, this reduction can be explained by a decrease in overlit areas, as excessively high illuminance levels above 3000 lux were removed in the improved case.

This suggests that, although the overall percentage of useful daylight has slightly decreased, the daylight conditions have become more acceptable and better aligned with recommended illuminance levels for exhibition spaces.


UDI......Exhibition area- Improved (50% skylight+new glazing wall)

64,9 % avg UDIa

89,2 % $sDA_{300/50\%}$

0,0 % $ASE_{1000,250}$

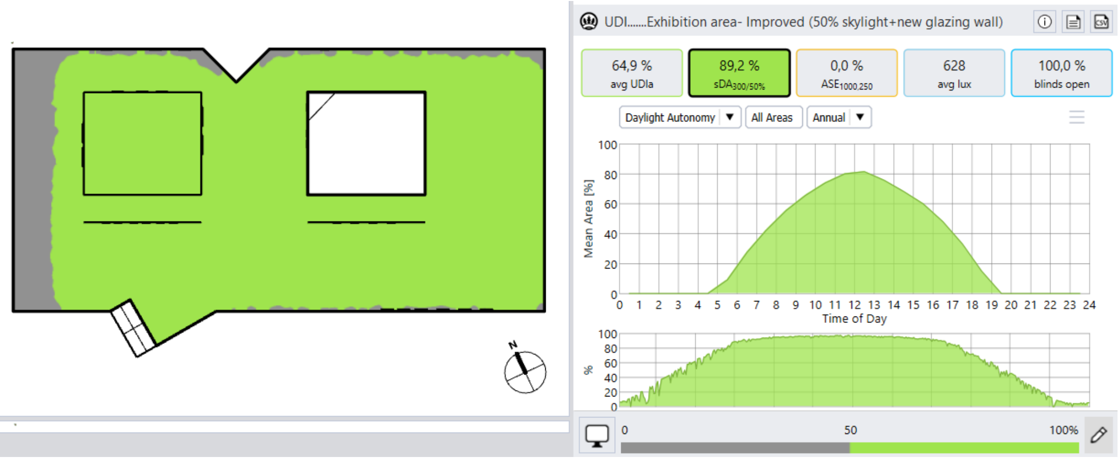
628 avg lux

100,0 % blinds open

Useful Daylight Illuminance ▼ | All Areas | Annual ▼

Figure 39. Spatial distribution of Useful Daylight Illuminance (UDI) in the exhibition area after improvement

Furthermore, the space achieved a high spatial daylight autonomy, with an sDA value of approximately 89.2% (Figure 40), indicating that most of the area is sufficiently daylit during occupied hours.



UDI......Exhibition area- Improved (50% skylight+new glazing wall)

64,9 % avg UDIa

89,2 % sDA300/50%

0,0 % ASE1000,250

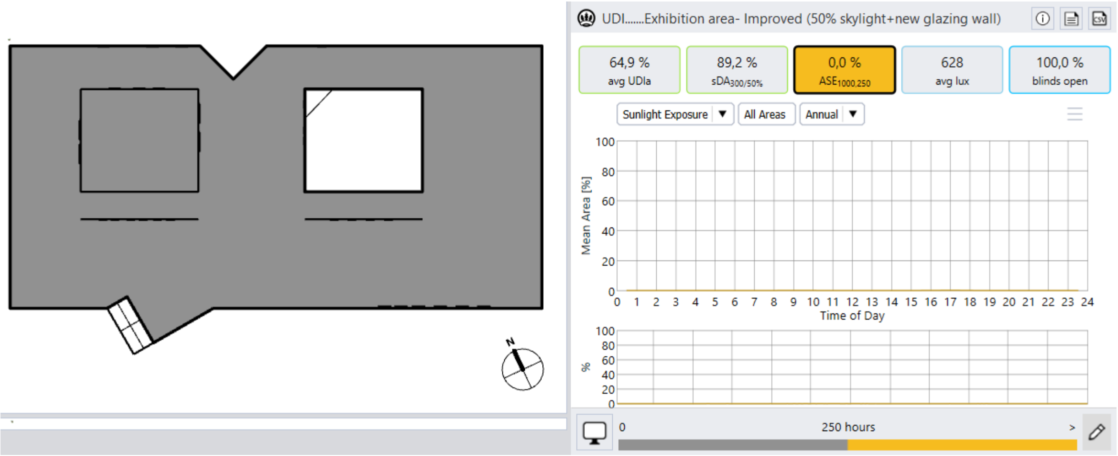
628 avg lux

100,0 % blinds open

Daylight Autonomy | All Areas | Annual

Figure 40. Spatial distribution of Daylight Autonomy (sDA) in the exhibition area after improvement

Figure 41 presents the Annual Sunlight Exposure (ASE), which was reduced to 0%, confirming that no areas are exposed to excessive direct sunlight throughout the year.



UDI......Exhibition area- Improved (50% skylight+new glazing wall)

64,9 % avg UDIa

89,2 % sDA300/50%

0,0 % ASE1000,250

628 avg lux

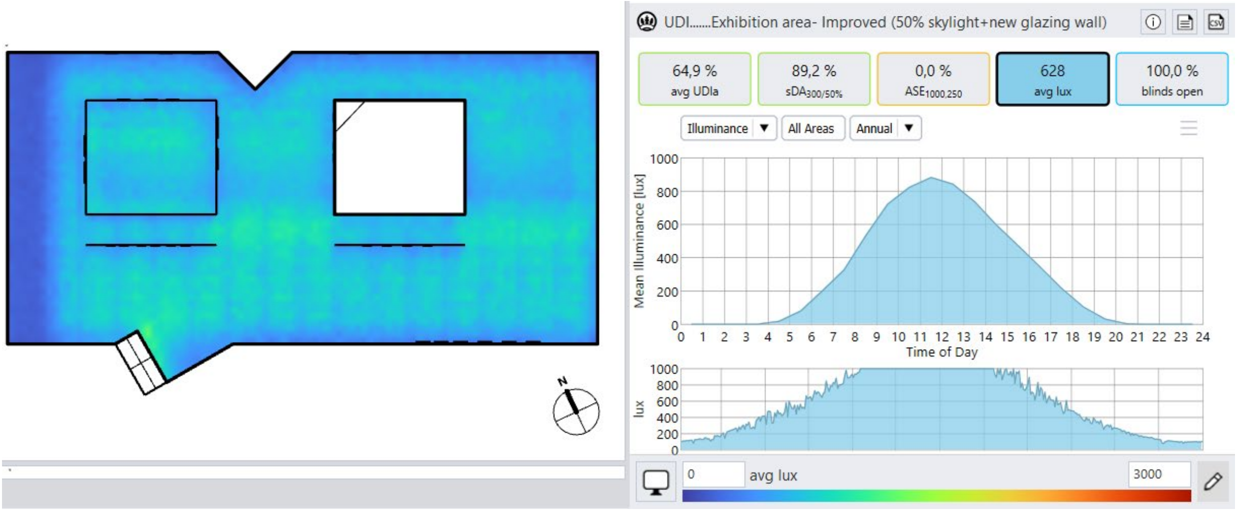
100,0 % blinds open

Sunlight Exposure | All Areas | Annual

Figure 41. Annual Sunlight Exposure (ASE) in the exhibition area after improvement

However, the average illuminance (avg lux) in the exhibition area remains relatively high at 628 lux (Figure 42). This value represents the average horizontal illuminance across the entire space rather than the direct illuminance on individual artworks. Compared to recommended illuminance levels for museum objects, which are typically between 200 and 300 lux for artworks with medium to low sensitivity, this value is higher. However, since vertical illuminance on artworks is generally lower than the overall horizontal illuminance within the space, the spatial average does not directly indicate the exact light exposure on individual artworks.

This suggests that while overall daylight levels in the space remain relatively high, the actual illuminance on artworks should be evaluated separately, as local conditions may vary depending on position, orientation, and exposure to daylight.


UDI.......Exhibition area- Improved (50% skylight+new glazing wall)

64,9 % avg UDIa

89,2 % $sDA_{300/50\%}$

0,0 % $ASE_{1000,250}$

628 avg lux

100,0 % blinds open

Figure 42. Annual average illuminance (lux) distribution in the exhibition area after improvement

The improved case presented in this section combines both daylight improvement measures described in Section 5.1, namely the skylight modification and the façade glazing modification. Therefore, the results represent the combined effect of these two strategies rather than the impact of each measure individually.

Table 16 summarises the main daylight performance indicators for both the base case and the improved case. The comparison highlights the effect of the implemented daylight improvement strategies on daylight availability, glare conditions, sunlight exposure, and overall illuminance levels within the exhibition space.

Table 16: Comparative summary of daylight performance results for the base case and improved case within the exhibition space

Parameter	**Base Case**	**Improved Case**	**Observation**
Mean Daylight Factor (DF, %)	6.2	4.0	Reduced daylight intensity and more controlled daylight conditions within the exhibition space
Median Daylight Factor (DF, %)	5.2	4.3	
Glare (sDGP > 5%, %)	2.4	0.0	Disturbing glare was eliminated after the implemented improvements
Useful Daylight Illuminance (UDI300–3000, %)	73.4	64.9	Useful daylight availability remained acceptable despite reduced daylight penetration
Spatial Daylight Autonomy (sDA300/50, %)	99.1	89.2	High daylight sufficiency was maintained across the exhibition space
Annual Sunlight Exposure (ASE1000,250, %)	0.8	0.0	Excessive direct sunlight exposure was fully reduced
Average Illuminance (lux)	926.0	628.0	Overall illuminance levels were reduced, resulting in more controlled lighting conditions

The comparison indicates that the implemented improvements reduced excessive daylight access and disturbing glare while maintaining acceptable daylight availability within the exhibition space. Although some daylight performance metrics decreased slightly, the improved case provided more controlled lighting conditions and improved visual comfort compared to the base case.

5.3 Improvement in energy use

A series of parametric simulations were conducted to analyse the influence of different parameters on overall energy performance. These parameters included improvements to the building envelope and the electric lighting system. Each measure was evaluated both individually and in combination to identify effective retrofit strategies. The improvement strategy followed a sequential approach: first, the thermal performance of the building envelope materials was enhanced, reducing heating demand; second, the light power density (LPD) was lowered, decreasing electric lighting use and total energy consumption; and finally, the skylight area was reduced and replaced with insulated roof construction.

The improvements are listed below:
1. Wall: Adding 300 mm mineral wool insulation.
2. Roof: Adding 250 mm mineral wool insulation.
3. Skylight: Blocking 50% of area for primary skylight, replacing it with original roof assembly.
4. Glazing: Improving the thermal properties of the glazing system (replacement with_Kalwall system).
5. Lighting system 1: 50% reduction in LPD achieved by halving the number of luminaires.
6. Lighting system 2: Adjusting lighting density to 6 W/m^2 according to ASHRAE Standard 90.1.

The above single-measure improvements can be grouped according to three parts: envelope improvement, skylight improvement, and lighting system improvement.

For skylight improvement, Figure 43 presents the simulation results.

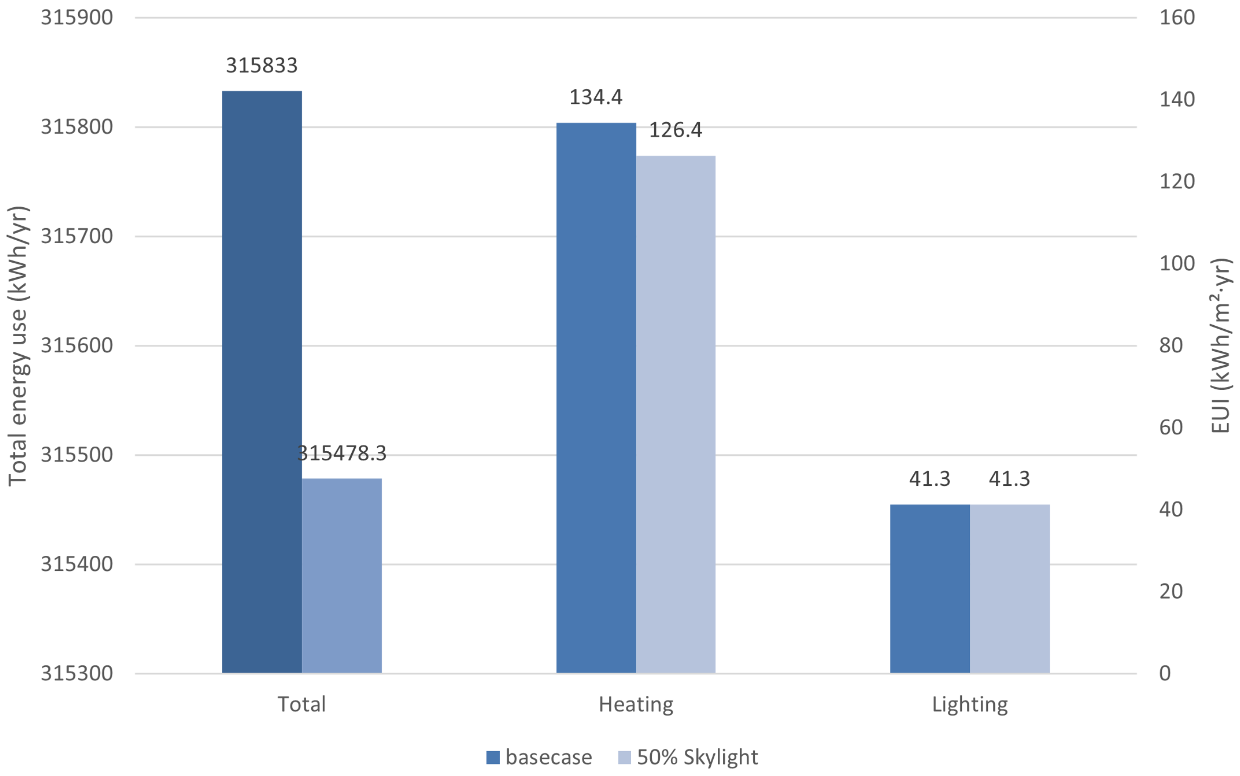


Figure 43. Comparison between the output from 50% skylight improvement and basecase (Single measure)

The results for envelope improvement are presented in Figure 44.

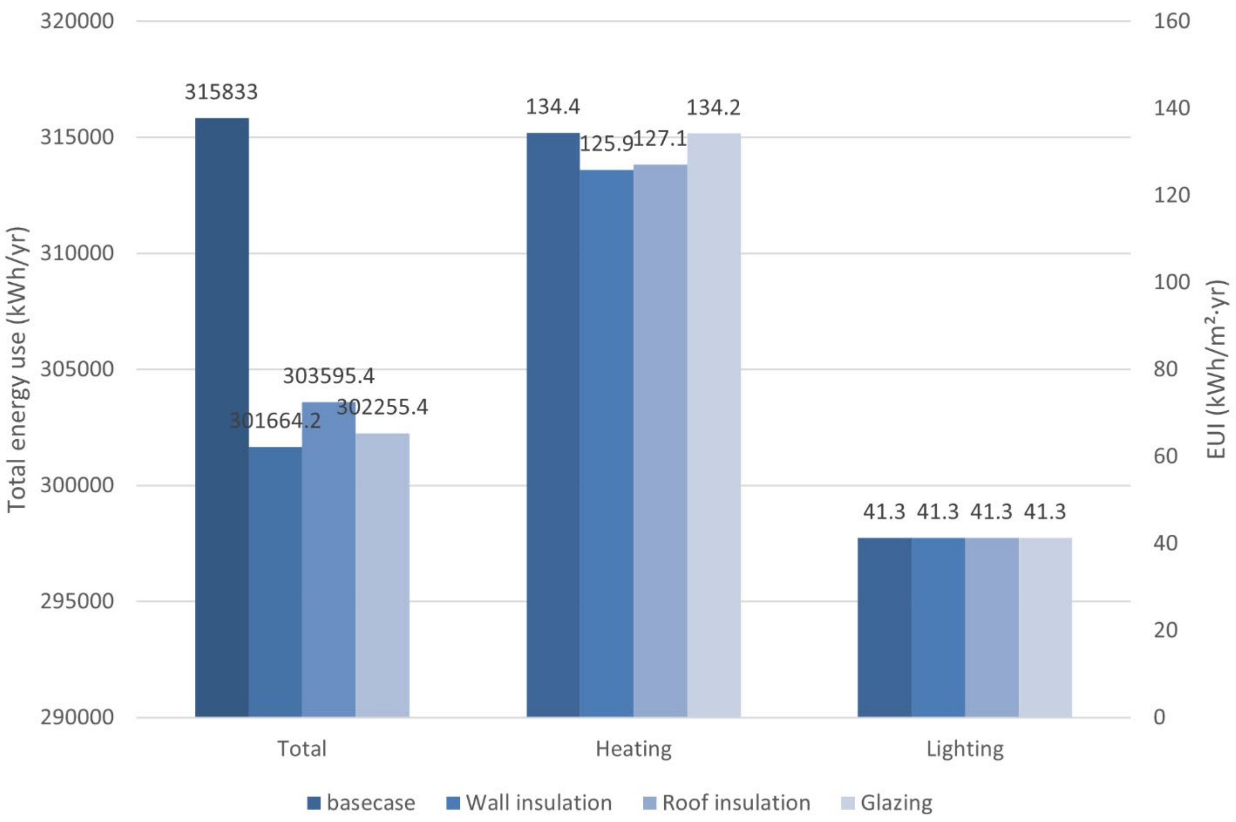


Figure 44. Comparison between the envelope optimization and basecase (Single measure)

The results for lighting system improvement are presented Figure 45.

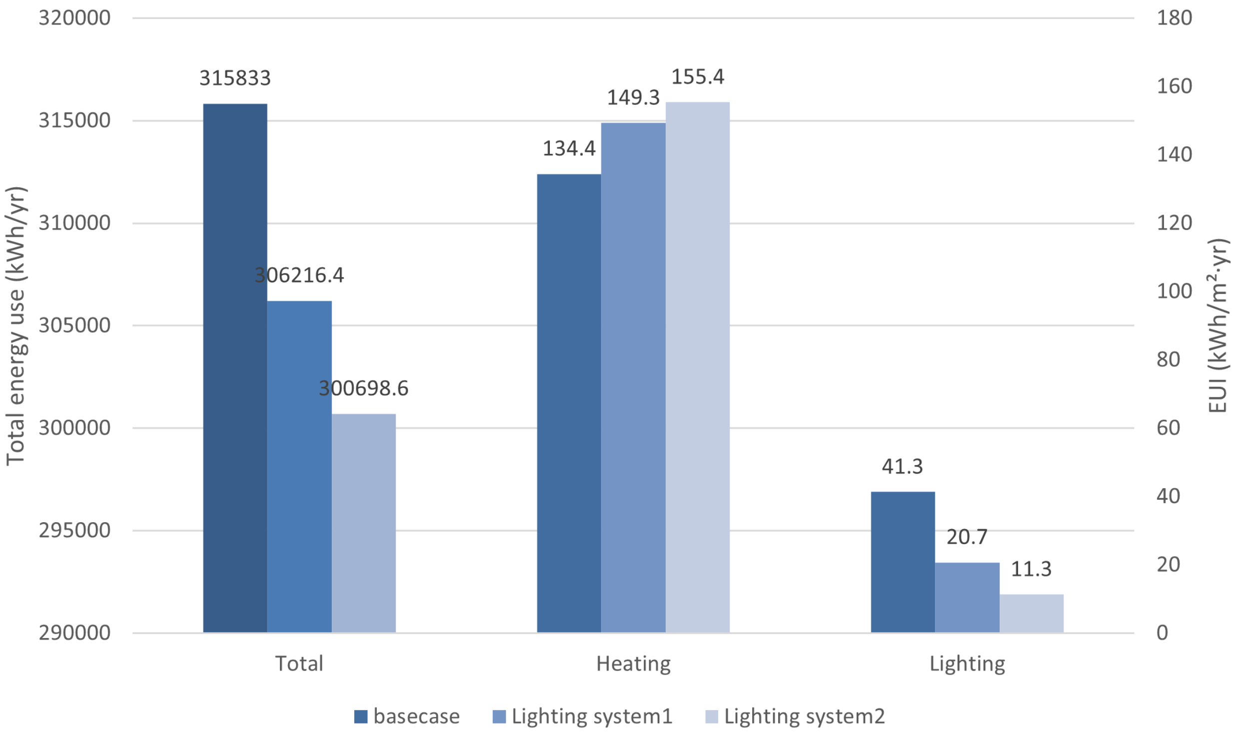


Figure 45. Comparison between the lighting improvement and basecase (Single measure)

From the perspective of total energy use, the installation of mineral wool insulation in the exterior walls is the most effective single-measure improvement. The reason is that exterior walls account for a substantial portion of the overall heat loss for the building, improving their thermal resistance leads to a noticeable reduction in heating demand. This explains the 4.5% decrease in total annual energy use observed in the simulations. In contrast, reducing the skylight area by 50% (replaced by original roof) results in only a 0.2% reduction in total energy use. The relatively small impact suggests that the skylight contributes slightly less to the overall heat loss compared to the walls, but the skylight area is 208.6m^2 compared to 851.6m^2 for the walls.

From the perspective of heating energy demand, wall insulation again proves to be the most effective measure, achieving a 6.4% reduction relative to the base case. Conversely, two lighting system improvements lead to 11% and 15% increase in heating load. This occurs due to the reduction of internal heat gain from lamps, which resulted in more requirements for heating.

Regarding lighting load, all measures except lighting system optimization have negligible direct impact. The lighting systems optimization successfully reduced lighting load by over 50%, demonstrating that this optimization is the most effective approach for reducing overall lighting load. This substantial reduction reflects the higher efficiency of the upgraded lighting systems and their ability to deliver the required illuminance with significantly lower energy input.

To further explore the potential for energy saving of this building, multiple retrofit measure optimization should be integrated. According to the single measure optimization results discussed above, skylight reduction demonstrates a marginal impact as a standalone improvement. This measure remains an important consideration due to its strong influence on daylight availability. Therefore, skylight area reduction should be included when developing and accessing multi measure optimization strategies. To investigate the contribution of different building components to the overall performance, two primary scenarios are considered for further analysis:

1. Scenario A: Envelope improvement integration
   This scenario aims to explore the maximum energy saving potential of the building envelope, without altering the performance of internal systems. It integrates all previously discussed improvements for opaque elements (wall and roof insulation) and transparent systems (high-performance glazing) with the 50% skylight reduction (replaced by insulated roof).

2. Scenario B: Total building integration
   Based on Scenario A, this scenario incorporates the optimization of the lighting system. As Lighting System 1 (reducing the number of luminaires) and System 2 (adjusting density according to ASHRAE 90.1) are mutually exclusive in practice, System 2 was selected for this integration due to its higher potential of energy saving. This scenario provides a comprehensive evaluation of the synergistic effects between the building envelope and high-efficiency lighting systems.

The results of multiple solutions are presented in Figure 46.

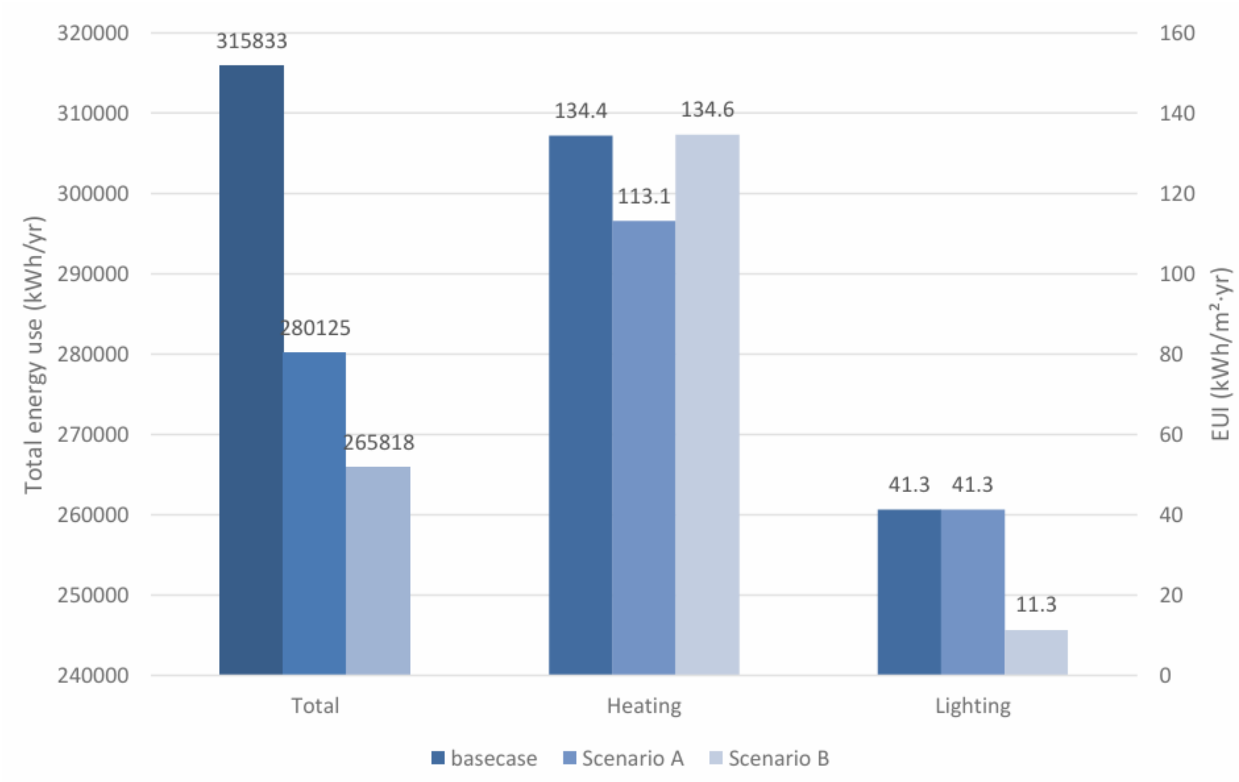


Figure 46. Comparison between the lighting improvement and basecase (Multiple measure)

Scenario A achieves substantial energy savings, reducing total annual energy use to 280,125kWh, which represents an 11.4% reduction compared with the base case (315,833 kWh). The heating EUI also decreases substantially, from 134.4 kWh/m²·yr to 113.1 kWh/m²·yr, corresponding to a 16% reduction. As expected, the lighting load remains unchanged, since the integrated envelope strategy does not directly affect lighting system efficiency.

Scenario B provides the largest energy-saving potential, with an annual energy use of 265,818 kWh, representing a 16.8% reduction compared to the base case. The lighting EUI decreases substantially from 41.3 kWh/m²·yr to 11.3 kWh/m²·yr, corresponding to a 72.6% reduction. However, the heating EUI shows a slight increase, likely due to the reduction of internal heat gains from electric lighting.

The results demonstrate the need for a holistic approach to building improvements. Enhancements to the lighting system should be accompanied by corresponding upgrades to the building envelope to avoid counterproductive effects. While single-measure interventions yield incremental benefits, integrated strategies provide a more substantial and balanced improvement in overall energy performance. This confirms that combining multiple measures unlocks the greatest potential for energy efficiency.

6. Discussion

The first research question (RQ1) was: "How can daylight conditions in a Nordic museum environment, represented by Malmö Konsthall, be assessed in terms of daylight quality, visual comfort, and energy performance? And what is the adequate methodology to evaluate daylight conditions?" The results suggest that daylight conditions can be effectively assessed using a combination of daylight metrics such as DF, UDI, sDA, ASE, and DGP, together with survey data. The case study demonstrated that relying on a single metric is insufficient, as different indicators capture different aspects of daylight performance, visual comfort, and artwork protection. In addition, the survey results provided valuable insights into visitors' perceptions that could not be obtained from simulations alone. The findings indicate that a combined methodology integrating simulations, measurements, and subjective evaluations provides a comprehensive approach for assessing daylight conditions in museum environments. Although this study focused on Malmö Konsthall, the methodology may also be relevant for evaluating daylight performance in other Nordic museums facing similar challenges related to daylight availability, visual comfort, artwork conservation, and seasonal variations in daylight conditions.

The second research question (RQ2) concerned the relationship between the answers to the questionnaire in the survey and the simulation-based analysis relying on daylight metrics. The results indicate that there is not always a complete agreement between simulation results and subjective evaluations. Results from the survey suggest that the lighting environment in Konsthall achieves both aesthetic appeal and functional requirements. The functionality of the illumination in Konsthall provides a good performance with a low score regarding flicker. And the score for hedonic tone indicates that this exhibition space provides positive feelings for visitors.

The light colour in Konsthall is reported as having a cool tone, which is in line with recommendations for museums. The colour tone has a benefit in increasing the colour accuracy of some specific exhibits. Furthermore, it enhances visual acuity and optimizes the emotional states of visitors, which provides deeper concentration.

The average brightness rating indicates that the space was perceived as adequately illuminated, which is in line with the simulation results showing sufficient daylight levels. In parallel, the hedonic tone value above the midpoint suggests that the lighting contributes to a positive emotional experience, providing both comfort and visual clarity.

The survey results offer valuable insights into how visitors perceive the lighting environment and serve as an important complement to the simulation-based analysis. Overall, participants evaluated the exhibition space positively, describing it as pleasant, sufficiently bright, and visually comfortable. Notably, even in areas where simulations indicated relatively high illuminance levels, respondents still reported a comfortable and visually pleasing environment. This suggests that moderate variations in daylight do not inherently cause discomfort, provided that glare and direct sunlight are effectively controlled.

Regarding the third research question (RQ3), which examined the current daylight conditions in Malmö Konsthall, the base- case analysis revealed that the building benefits from generally high daylight availability but lacks adequate control mechanisms. Several artworks were exposed to illuminance levels exceeding recommended thresholds, particularly in areas adjacent to skylights and glazed facades. These findings indicate that, although the space is well daylit, daylighting is in many cases overabundant. The results of this study therefore highlights a dual role of daylight in the exhibition environment: it enhances visitor experience and can reduce energy demand, yet it must be carefully managed to prevent adverse effects on light sensitive artworks.

The fourth research question (RQ4) examined how skylights influence daylight distribution and visual comfort in the exhibition space. The results confirm that skylights have a substantial impact on both aspects. In the base case, direct daylight entering through the skylights produced high illuminance levels and pronounced contrast. The improvement strategies therefore focused on mitigating excessive light levels, particularly on the artworks. The most effective solution combined two measures: replacing the lower portion of the skylight with insulated roof assembly and changing the facade glazing. Together, these interventions reduced the amount of direct daylight entering the space and significantly lowered the illuminance levels on most artworks.

In addition to improving conditions for the artworks, the proposed modifications also influenced the overall exhibition environment. In the improved case, the space achieved high daylight availability (sDA) while eliminated both glare and excessive sunlight exposure (ASE), indicating a more visually comfortable setting for visitors. However, the average illuminance across the space remained relatively high, suggesting that the environment continues to be quite bright despite the interventions. From a museum perspective, this is generally a favourable outcome: the low ASE value signals a minimum risk of excessive solar exposure, thereby reducing glare and limiting potential damage to light-sensitive artworks. Nonetheless, areas near the façade may still require careful consideration due to localized instances of direct sunlight.

This highlights a key point: improving daylight conditions in museums is not simply a matter of increasing or reducing light levels, but about achieving an appropriate balance between visibility, visual comfort, and the preservation of artworks.

Finally, the fifth research question (RQ5) examined the impact of daylight design on energy use, including electric lighting and heating. The results demonstrate that daylight design has a measurable influence on overall building energy performance. Measures such as facade improvements and reductions in skylight area affected not only daylight conditions but also heating demand. While individual interventions produced relatively modest changes, combined strategies led to a more substantial reduction in total energy use, underscoring the importance of integrated design solutions.

According to the simulation results, installing wall insulation yields the most significant improvement among the single-measure interventions. These findings suggest that the primary limitation to energy efficiency in Malmö Konsthall is associated with the thermal performance of the building envelope. As part of the envelope-related strategies, the replacement of the existing glazing with high-performance Kalwall translucent insulation panels was also evaluated.

Although reducing the primary skylight area alone results in only a negligible reduction in total energy use, this measure demonstrates a synergistic effect when combined with envelope improvements. When wall insulation and skylight reduction are implemented together, the total energy savings increase to 6.3%, exceeding the impact of either measure individually. Integrated improvement strategies address multiple sources of heat loss simultaneously, leading to more effective and robust energy performance outcomes.

Furthermore, the lighting improvement scenarios reveal a negative correlation between lighting power density and heating demand. As the lighting power density decreases, the internal heat gains from electric lighting are reduced, resulting in an increase in heating load. These results highlight the complex relationship between thermal losses and luminous transmission in Malmö Konsthall. They illustrate that the benefits of isolated single-measure improvements can be diminished by other interacting factors within the building system. The lighting system upgrades should be implemented in conjunction with enhancements to the thermal properties of the building envelope. A holistic approach ensures that the energy savings achieved through more efficient lighting are not offset by increased heating requirements.

Overall, this study demonstrates that effective daylight design in museums is not about maximizing daylight, but about achieving an appropriate balance that ensures good visibility while protecting artworks and maintaining reasonable energy use. The findings also show that combining simulation results with subjective evaluations provides a more comprehensive understanding of the daylight conditions within the space.

7. Conclusions

7.1 Main Findings

- Daylight levels in Malmö Konsthall are generally high but require additional control to comply with museum lighting recommendations for artworks.

- Skylights strongly influence daylight distribution, contributing to both high daylight availability and relatively uniform lighting conditions.

- The implemented improvement strategies reduced excessive illuminance and glare while maintaining useful daylight within the exhibition space.

- Daylighting and lighting strategies have a direct impact on energy performance, particularly with respect to heating demand.

- Enhancing lighting energy efficiency should be combined with building envelope improvements to avoid unintended increases in heating demand.

- The survey results generally supported the simulation-based analysis, indicating that combining objective and subjective evaluation methods provides a more comprehensive understanding of daylight quality and visual comfort in museum environments.

- Although this study focused on Malmö Konsthall, the findings provide broader insights for Nordic museums. Skylight-dominated museum designs can provide high daylight availability, but daylight control strategies are often required to reduce excessive illuminance on artworks. The results also highlight the importance of evaluating daylight and energy performance together in Nordic climates characterised by large seasonal variations in daylight availability.

7.2 Limitations

This thesis has several limitations that should be considered when interpreting the results. The study focuses on a single case study, Malmö Konsthall, which means that the findings cannot automatically be generalized to all museum buildings. However, the selected case represents a large Nordic exhibition space where daylight and energy performance are closely connected.

Although both daylight and energy use are analysed, the research. Energy performance is evaluated through building performance simulations and calculated energy indicators, but some operational factors, such as detailed HVAC behaviour and real-time control systems, are not fully modelled. Therefore, the energy results should be understood as performance-based estimations rather than exact operational data.

In addition, the accuracy of both daylight and energy analysis depends on the quality of available drawings, modelling assumptions, and input data. Changes in exhibition layouts, temporary installations, and internal heat gains may influence real performance conditions but are difficult to fully represent in simulations.

The definition of occupancy hours used in the daylight simulations also represents a limitation. The analysis is based on the official museum opening hours (11:00–17:00), which reflect the typical visitor period. However, the spaces may also be used by staff outside these hours for activities such as preparation, maintenance, or installation of artworks. Including these additional hours could influence the daylight performance results, particularly metrics such as spatial daylight autonomy (sDA), as daylight availability is generally lower in early morning and late afternoon periods. As a result, the reported daylight performance may be slightly overestimated.

Finally, the visitor perception data is based on a short survey with limited responses, which provides qualitative insight into visual comfort but does not allow for statistical generalization. Despite these limitations, the combined evaluation of daylight performance, energy use, architectural analysis, and user perception provides a comprehensive and relevant basis for addressing the research questions of this study.

7.3 Future Research

This study highlights several areas that could be further developed in future research. First, the results are based on a single case study, Malmö Konsthall. Future studies could include multiple museum buildings in different Nordic locations to allow for broader comparisons and more general conclusions.

In addition, the current research includes both daylight performance and energy use, with a specific focus on reducing the heating demand. However, future work could include more detailed dynamic energy simulations, considering HVAC systems, real operation schedules, and advanced control strategies. This would provide a deeper understanding of how daylight design decisions influence the heating demand and overall energy performance.

Furthermore, future studies could include more participants in the survey. This would help to get more reliable results and a better understanding of how people experience daylighting in museum spaces.

Finally, future research could explore more advanced strategies that integrate both daylight and energy performance, such as adaptive shading systems, improved glazing technologies, and climate-responsive design solutions. Future studies could also include cost analysis and life-cycle assessment (LCA) of the proposed interventions to better evaluate their long-term environmental and economic impacts. These approaches could help achieve a better balance between visual comfort, artwork protection, and reduced heating demand.

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Appendix A: Belupp questionnaires & definitions (adapted from Parvathy et al., 2023)

Miljöpsykologi, LTH, 1995 Datum:

HOW DO YOU PERCEIVE THE LIGHTING CONDITIONS IN THIS ROOM

Mark by ticking the scales below

Dark	☐	☐	☐	☐	☐	☐	☐	Light
Pleasant	☐	☐	☐	☐	☐	☐	☐	Unpleasant
Uncoloured	☐	☐	☐	☐	☐	☐	☐	Coloured
Strong	☐	☐	☐	☐	☐	☐	☐	Weak
Scattered	☐	☐	☐	☐	☐	☐	☐	Concentrated
Warm	☐	☐	☐	☐	☐	☐	☐	Cool
Uneven distributed	☐	☐	☐	☐	☐	☐	☐	Even distributed
Hard	☐	☐	☐	☐	☐	☐	☐	Soft
Unfocused	☐	☐	☐	☐	☐	☐	☐	Focused
Natural	☐	☐	☐	☐	☐	☐	☐	Unnatural
Flicker	☐	☐	☐	☐	☐	☐	☐	No Flicker
Clear	☐	☐	☐	☐	☐	☐	☐	Darb
Varied	☐	☐	☐	☐	☐	☐	☐	Monotonous

Mild	☐	☐	☐	☐	☐	☐	☐	Sharp
Glaring	☐	☐	☐	☐	☐	☐	☐	Shaded
Subdued	☐	☐	☐	☐	☐	☐	☐	Brilliant

HOW WELL DO YOU COULD SEE IN THESE LIGHTING CONDITIONS?

Very bad	☐	☐	☐	☐	☐	☐	☐	very good

Belupp questionnaires Definition:

Dark - with little or no light

Light - having sufficient amount of natural light to make things visible

Pleasant - light giving a sense of happy satisfaction or enjoyment

Unpleasant - light causing discomfort or unhappiness

Uncoloured - light having no colour or neutral in colour

Coloured - light having a colour or colours as opposed to being black, white, or neutral

Strong - light showing a characteristic in extreme degree

Weak - diminishing the strength or brilliance of light

Scattered - light reflecting irregularly and diffusely

Concentrated - pinpointed beam of light

Warm - light with red, orange, and yellow tones

Cool - light with blue tones

Uneven distributed: light varying in quality

Even distributed - light unchanging in form or character

Hard - light making distinct, hard-edged shadows

Soft - light making shadows barely visible

Unfocused - light having an indistinct and hazy appearance

Focused - pinpointed beam of light

Natural - light from the sun

Unnatural - light from electric (electric) luminaires

Flicker - unsteady movement of light causing rapid variations in brightness

No flicker - steady movement of light with no variations in brightness

Clear - light free from cloudiness

Darb - light lacking brightness or interest

Varied - light changing in colour and intensity

Monotonous - light lacking in variety or interest

Mild - softer light with a cozier feel

Sharp - crisper, fresher light

Glaring - light that enters your eye and impedes your vision performance or causes discomfort

Shaded - relative darkness produced by the blocking out of light

Subdued - not bright light

Brilliant - bright/intense light

Appendix B: Site visit photographs

Figure 47. Exterior view of Malmö Konsthall during the site visit.

Figure 48. Interior exhibition space showing partially covered skylight openings used to control daylight penetration

Figure 49. Large skylight glazing system providing daylight penetration into the exhibition space

Figure 50. Exhibition hall showing daylight distribution from the large skylight glazing

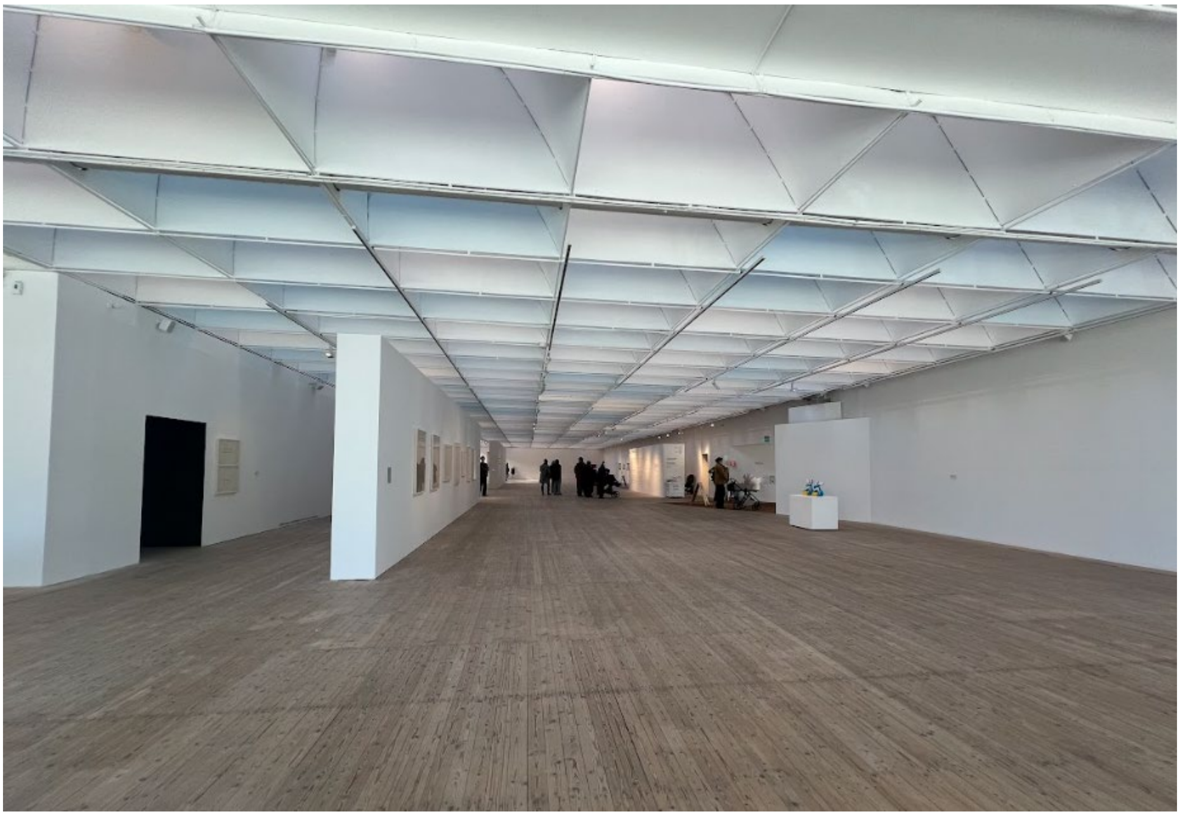

Figure 51. Main exhibition hall with diffuse daylight distribution from the ceiling system

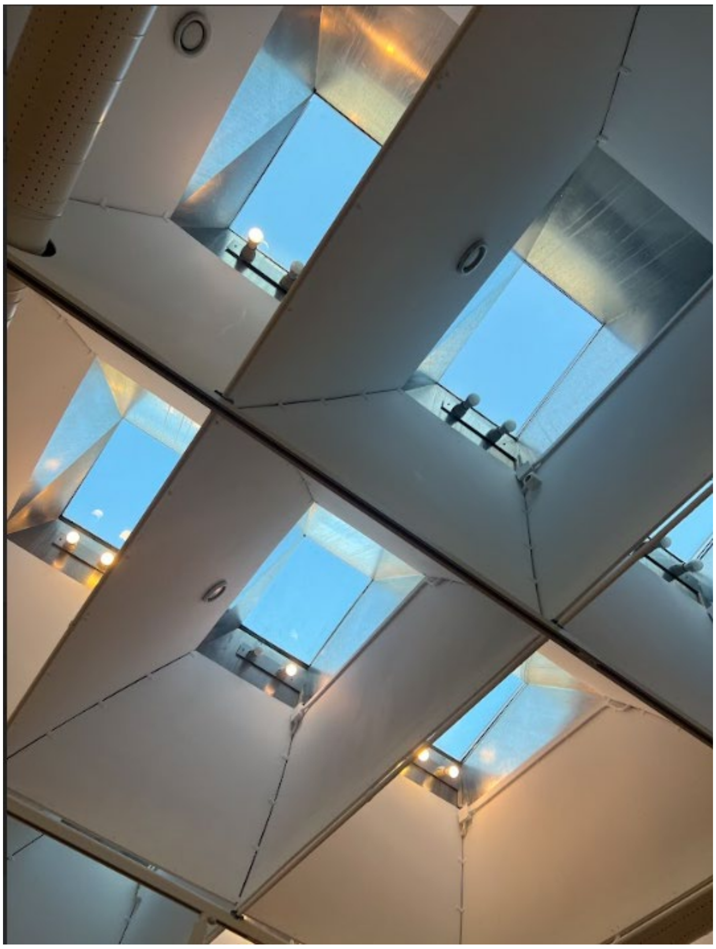

Figure 52. Detail of the skylight construction and ceiling daylight system

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