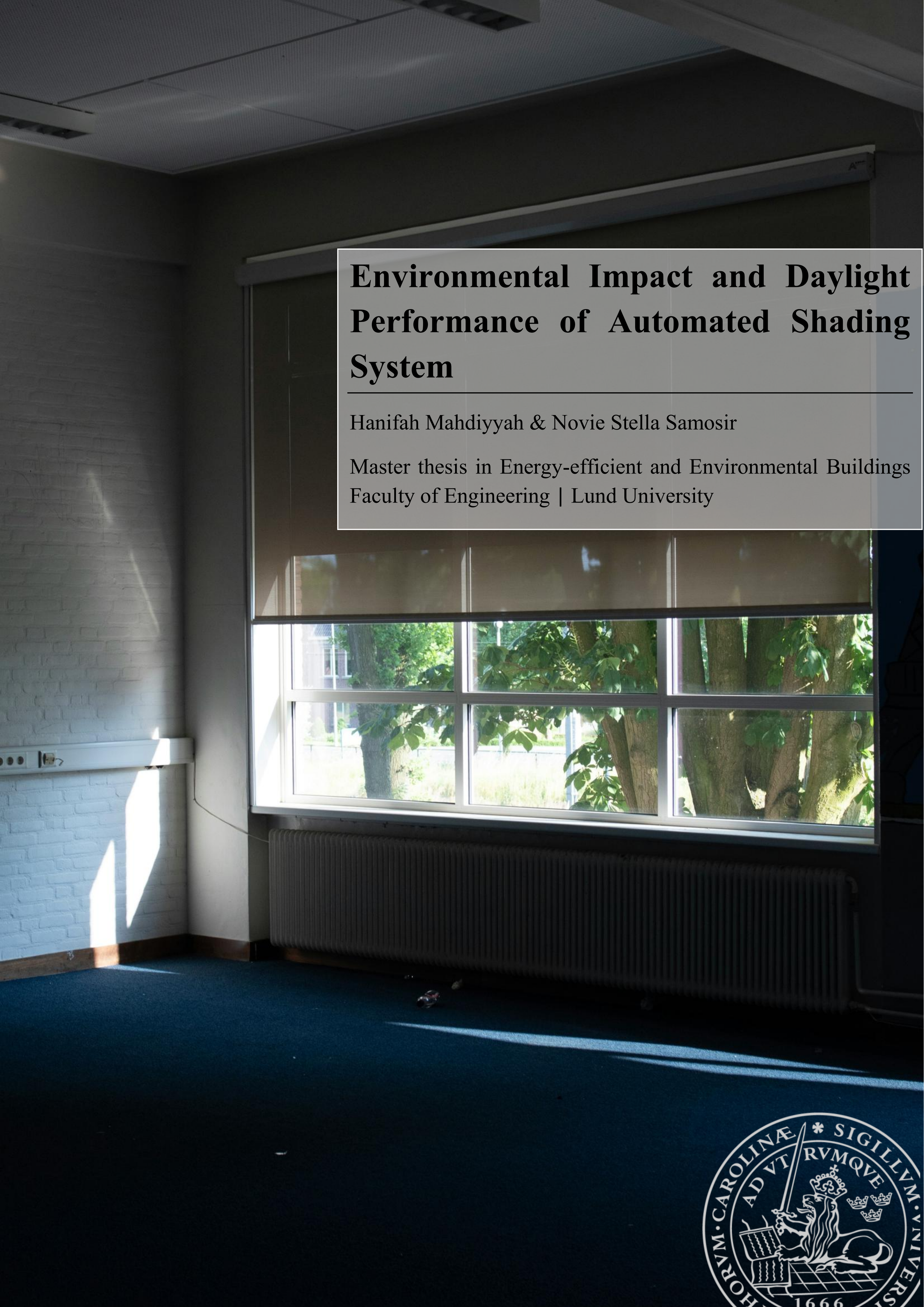

Environmental Impact and Daylight Performance of Automated Shading System

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

Lund University

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

Master Programme in Energy-efficient and Environmental Building Design

This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

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

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Keywords: automated façade shading, daylight performance, fenestration system, Energy Use Intensity (EUI), Global Warming Potential (GWP)

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Abstract

As buildings become more energy-efficient in their operation, the environmental costs of building components, such as carbon emissions during manufacturing, transportation, and end-of-life, are becoming increasingly significant. Automated façade shading systems have been widely proposed for their ability to reduce operational energy use and improve daylight performance. However, their life-cycle environmental impacts are rarely studied alongside their operational benefits. This study addresses this gap.

This thesis evaluates the daylighting performance, energy use, thermal comfort, and life-cycle environmental impacts of manual and automated façade shading systems in a reference office space in Lund, Sweden. Three shading types were evaluated: External Venetian Blinds (EVB), External Roller Blinds (ERB), and Interior Roller Blinds (IRB), each combined with three types of glass and two control strategies (manual and automated), resulting in 55 scenarios including a baseline scenario with no shading in the simulation.

Climate-based daylight simulations were used to assess daylight availability using Spatial Daylighting Autonomy (sDA) to assess how well-lit the room is by daylight and Useful Daylight Illumination (UDI) as an indicator leading to glare risk. Energy performance was evaluated using dynamic building simulations to estimate energy use for heating, cooling, lighting, and electrical equipment, and by calculating overheating hours as an indicator of thermal comfort. A Life Cycle Assessment (LCA) was then conducted following ISO 14040 and EN 15978, focusing on Global Warming Potential (GWP) expressed in $kgCO_2eq/m^2floor/year$, covering life cycle stages A1–A5, B2, B6, and C2–C4.

The results indicated that automated shading generally improved daylight distribution and decreased cooling needs compared to manual control methods. However, some of the shading configurations, such as fully covered blinds, tend to increase lighting energy consumption and overall energy use. Among the shading types evaluated, automated External Venetian blinds (EVB) set at a 45° angle combined with coated float glass achieved the best overall energy performance. From a life-cycle perspective, most scenarios involving automated external shading systems show a lower total Global Warming Potential (GWP) than manual systems, with a difference of 0.04-1.88 kgCO2eq/m2floor/year, despite the additional embodied carbon from components such as motors, gateways, and sensors. These results underline the importance of evaluating daylight performance, energy use, and life cycle Assessment (LCA) calculations when designing facade systems for energy-efficient offices.

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Last but not least, we want to thank our family for their unconditional love and support. Even with a big-time difference, they never stop showing their presence and give us motivation to become the best of ourselves. Thank you!

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Abbreviations

Abbreviation	Full Term
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BBR	Boverkets Byggregler (Swedish Building Code)
CBDM	Climate-Based Daylight Modelling
COP	Coefficient of Performance
DA	Daylight Autonomy
EN	European Standard (Euronorm)
EPD	Environmental Product Declaration
EPW	EnergyPlus Weather file
ERB	External Roller Blind
EUI	Energy Use Intensity
EVB	External Venetian Blind
FU	Functional Unit
GWP	Global Warming Potential
HVAC	Heating, Ventilation and Air Conditioning
IEQ	Indoor Environmental Quality
IES	Illuminating Engineering Society
IRB	Interior Roller Blind
ISO	International Organisation for Standardisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEED	Leadership in Energy and Environmental Design
PEP	Product Environmental Profile
sDA	Spatial Daylight Autonomy
UDI	Useful Daylight Illuminance
USGBC	US Green Building Council
WWR	Window-to-Wall Ratio

1 Introduction

This chapter presents the background and motivation of this study, defines the research questions and objectives, and outlines the scope and limitations of this work.

1.1. Background and Motivation

The building sector has a significant impact on the environment, with heating and cooling representing the largest portion of energy use. Globally, buildings are responsible for about 40% of total energy use and greenhouse gas (GHG) emissions (Ohene, et al., 2022). In this context, facades play a central role in regulating the exchange of heat, light, and air between the building interior and the external environment, thereby directly influencing energy demand and the quality of the indoor environment.

Automated façade shading systems are an effective way to boost building energy performance. Automated systems can be adjusted in response to environmental conditions and occupant needs. These systems manage solar energy gains and affect various indoor environmental quality aspects, including daylight availability, thermal comfort, natural ventilation, humidity, external views, and even outdoor noise (de la Barra, et al., 2025). Typically, automated shading systems monitor environmental conditions and adjust shading elements automatically (Gonçalves, et al., 2024). Automated shadings are especially relevant in office buildings with large glazing facades, where uncontrolled solar radiation can cause overheating, glare, and high energy use (Bülow-Hübe, 2008).

However, automated shading systems are not simple products. They consist of motors, sensors, gateways, and electronic control components, all of which require energy and raw materials for production, transport, and disposal. As buildings become more operationally efficient, their contribution to the whole building embodied carbon increases. Shading systems that save operational energy may still have significant environmental impacts when their overall life cycle impacts are considered. The tension between operational savings and the inherent environmental impact is rarely examined in the literature (Do & Chan, 2020; Igrexas, 2024).

This study addresses this gap by simultaneously evaluating daylight performance, energy use, thermal comfort, and life cycle environmental impacts of both manual and automated control facade shading strategies in a single office setting. The results emphasize the need for a more comprehensive approach to facade design that considers not only operational energy savings but also the overall environmental impact of shading systems.

1.2. Research Questions

This study aims to highlight the trade-offs between daylight performance, thermal comfort, energy demand, and environmental impact of manual and automated façade shading systems. The objective is addressed by evaluating the performance of an exemplary manual and automated façade shading systems in a Swedish individual office context.
Specifically, the study addresses the following research questions:

1. How do different automated façade shading types and configurations influence daylight performance in terms of sDA and UDI?
2. How do these shading types and configurations affect thermal comfort, particularly in overheating hours?
3. How do these shading types and configurations compare in terms of environmental impact?
4. What trade-offs emerge between daylight performance, thermal comfort, energy demand, and environmental impact, considering that the numerical results are specifically applicable only to the case study examined?

1.3. Goal

This study aims to evaluate the performance of automated facade shading systems in an office context, by comparing manual and automated control strategies across various facade system configurations. The analysis examines how these configurations impact daylight availability, thermal comfort, energy use, and environmental impacts throughout their lifecycle. The findings are intended to support architects, facade engineers, and building designers in making more informed decisions about shading system selection, particularly when considering the operational energy benefits of automation against the carbon costs over the systems' lifecycle.

1.4. Scope

This study focuses on a representative office space located at the Energy and Building Design (EBD) Laboratory in Lund, Sweden. Three types of window coverings, namely External Venetian Blinds (EVB), External Roller Blinds (ERB), and Interior Roller Blinds (IRB), were evaluated under manual and automatic control strategies. The simulations include a baseline with no shading and 54 shading system configurations.

Performance was assessed in three areas: daylighting performance (using sDA and UDI metrics), energy performance (heating, cooling, lighting, and equipment energy use), and environmental performance (GWP, expressed in $kgCO_2eq/m^2$ of shading system). The life cycle assessment, following ISO 14040 and EN 15978, covers the product stage (A1–A3), the construction stage (A4–A5), the maintenance stage (B2), the operational energy use (B6), and the end-of-life stage (C1–C4). Detailed information on functional units, system boundaries, inventory data, and impact assessment methods is provided in the methodology chapter.

1.5. Limitations

This study has several limitations that should be considered when interpreting the results:

1. This study is based on one reference office space facing South with a window-to-wall ratio of 70%, higher than in typical office buildings (30–40%). This means the results may not be applicable to buildings with different designs, orientations, or climate conditions.
2. Different modelling approaches were applied to energy and daylight simulations due to software limitations. Energy simulations use a simplified representation of shading behaviour, while daylight simulations require geometric modelling of shading configurations to accurately capture solar radiation penetration. As a result, consistency between energy and daylight models is limited.
3. Daylight-responsive lighting control is not explicitly simulated in the energy simulation because lighting energy output remains constant due to the constant lighting schedules in a year across all scenarios. Therefore, lighting energy demand is calculated using the Daylight Autonomy (DA) metric, which represents daylight availability.
4. The LCA uses a mix of Environmental Product Declarations (EPDs) for building products and Product Environmental Profiles (PEPs) for automation components. These two declaration types may use different background databases, which introduces minor uncertainty in data quality.
5. The performance of the automated shading system was evaluated using a control schedule determined based on solar radiation threshold. Meanwhile, the manual shading system used a schedule generated based on the illuminance threshold on desks in the office space. This approach allows for a more consistent definition of the performance of the shading control systems.
6. Emission factors for the electricity grid (0.115 $kgCO_2/kWh$, Öresund mixture) and district heating (0.011 $kgCO_2/kWh$) are assumed to be constant over the 30-year study period. In practice, the electricity grid decarbonisation will reduce operational carbon over time.
7. This study only assessed Global Warming Potential (GWP) as the LCA impact category. This is the most commonly reported impact in building LCA and the one most relevant to climate policy.

2. State of The Art

This chapter presents the relevant literature for this study. It begins with an overview of facade systems, shading devices, and control strategies, covering both automated and manual approaches. Then discusses the methods and metrics used to assess daylight performance in office environments. In the end, the chapter concludes with a review of Life Cycle Assessment (LCA) applied to building components, specifically automated facade systems.

2.1. Façade Systems, Shading Devices, and Control Strategies

A complete device that includes glazing and shading devices on a building facade can be called a fenestration system. It regulates the flow of solar radiation, daylight, and heat between interior and outdoor environments, directly affecting energy performance, thermal comfort, and visual comfort. In office buildings, the fenestration system is one of the most influential design parameters, especially when a large glazed area is used to provide daylight and outdoor views (Bülow-Hübe, 2008).

Facade shading devices play a crucial role in regulating the amount of solar radiation entering a building, thereby affecting daylight availability, thermal performance, and overall energy use (Bellia, et al., 2014). Shading systems help control sunlight penetration by reducing excess heat, glare, and improving indoor environmental quality. At the same time, shading systems influence the spatial distribution of daylight within interior spaces and the visual connection between occupants and the outdoor environment.

Shading devices are typically classified by position and operation. Based on position, they are categorized as external or internal. External shading devices are generally more effective at reducing solar heat gain by blocking radiation before it reaches the glass surface (Poirazis, Blomsterberg, & Wall, 2008), although they may increase dependence on artificial lighting. In contrast, internal shading devices are less effective at limiting heat gain but are important for glare control, privacy, and visual comfort, especially at low sun angles prevalent in higher latitudes (Czachura, 2019).

Operationally, shading devices may be fixed or movable, and can be controlled either manually or automatically. Fixed shading provides consistent sun protection but lacks adaptability to changing environmental conditions. In contrast, movable shading systems offer greater flexibility, enabling performance adjustments in response to variations in sun position, climate, and occupant requirements

Beyond classification, the performance of shading systems depends on configuration parameters such as slat angle, shade coverage, screen depth, and material reflectivity. These factors determine how solar radiation is transmitted, reflected, or redirected into interior spaces (Samadi, et al., 2020). For instance, optimizing louver tilt angle, screen depth ratio, and reflectivity can enhance daylight penetration while minimizing glare. Adaptive blind systems that adjust slat rotation and spacing according to the sun's position can further improve daylight distribution and prevent direct glare by redirecting sunlight into interior surfaces (Samadi, et al., 2020).

Given the numerous influencing factors, shading design is a multi-objective challenge that requires balancing daylight availability, glare control, thermal performance, and energy consumption. Additionally, occupant interaction introduces further complexity, as user behavior can significantly affect the effectiveness of shading. Consequently, integrating appropriate control strategies is essential to ensure the effective operation of shading systems under diverse environmental and occupancy conditions.

2.1.1. Automated Façade System

Dynamic and automated facade systems are under investigation as solutions to enhance building energy performance and indoor environmental quality. In contrast to manually operated systems, automated shading devices operate according to predetermined control strategies that use solar radiation, indoor illumination, temperature, and the glare index to adjust shading configurations in real time.

Research has shown that automated facade systems can enhance building performance relative to static or manually controlled shading systems. Automated shading has been shown to reduce cooling energy requirements by 0–40%, depending on climatic conditions and facade orientation, with higher reductions reported in specific cases (de la Barra, et al., 2025). Additionally, significant reductions in lighting energy consumption have been observed when automated systems are designed to optimize natural light usage, with reported savings of approximately 30% compared to unshaded or static facade conditions (de la Barra, et al., 2025). These performance improvements, however, depend heavily on the chosen control strategy and assumptions regarding occupant interaction.

A range of control strategies has been developed to regulate automated shading systems. Rule-based control, the most prevalent approach, triggers shading operation based on threshold values of environmental variables such as work surface illumination or solar radiation. More advanced methods include model-based and predictive control systems that use simulated data or optimization algorithms to determine optimal shading positions. Recently, machine learning-based strategies have been explored to enhance system responsiveness by predicting occupant preferences and environmental conditions (Luo, Sun, & Dong, 2020).

Despite their potential, automated facade systems present several challenges. A significant limitation identified in the literature is the discrepancy between simulation-based results and actual performance. In certain cases, increased dissatisfaction with daylighting conditions has been reported under fully automated controls, indicating that control objectives may not consistently align with occupant preferences. Allowing occupants to override automated controls often results in reduced energy savings, underscoring the importance of user-centered control design (de la Barra, et al., 2025). Additionally, automated systems may not consistently address occupant preferences, particularly concerning visual comfort and access to outdoor views.

Furthermore, most studies focus on single-objective control strategies, such as maximizing daylight availability, reducing glare, or minimizing cooling requirements. However, these objectives are inherently interdependent, and optimizing one aspect can adversely affect others. As a result, there is an increasing need for integrated, multi-objective control strategies that simultaneously address daylight performance, thermal comfort, and energy efficiency.

In summary, although automated facade systems offer considerable potential to improve building performance, their effectiveness depends on control logic, system configuration, and occupant interaction. Careful consideration of these factors is essential to achieve a balanced and reliable facade design.

2.1.2. Manual Façade System

Manual facade control systems depend on occupant interaction to adjust shading devices in response to indoor environmental conditions. Previous research indicates that in office settings, occupants generally adjust blinds to mitigate discomfort caused by excessive sunlight, glare, or elevated solar heat gain. Among these factors, solar irradiance is frequently used as an indicator for modeling blind operation behavior because it directly relates to visual discomfort and increased solar heat gain (Verma & Gopalakrishnan, 2025). However, occupant responses vary and are often inconsistent, making manual control inherently unreliable.

In building performance simulations, several Occupant Behavior-Controlled Blinds Models (BC-OBM) have been developed to represent occupant-driven shading behavior (Verma & Gopalakrishnan, 2025). Among these, Reinhart introduced a widely adopted stochastic model that assumes blinds are adjusted according to the level of solar radiation incident on the work surface (Reinhart C. F., 2004).

The Lightswitch-2002 approach specifies that blinds are closed when direct solar radiation on the work surface exceeds a defined threshold, typically around 50 W/m², and are reopened at the beginning of the next occupancy period. This rule-based behavior reflects a common real-world pattern in which occupants close blinds to avoid discomfort and often leave them closed for extended periods rather than making frequent adjustments (Reinhart C. F., 2004).

Despite its simplicity, the Lightswitch-2002 model captures a key aspect of manual control: occupants do not continuously optimize shading performance but instead react periodically to discomfort. This behavior frequently results in reduced daylight availability and greater reliance on artificial lighting, which contributes to discrepancies between predicted and actual building performance (Reinhart C. F., 2004).

Studies indicate that omitting occupant behavior models or oversimplifying manual control assumptions in simulations can lead to significant errors in daylighting and energy predictions, thereby contributing to the energy performance gap (Verma & Gopalakrishnan, 2025). Therefore, incorporating an occupant-based control model, such as Lightswitch-2002, is essential for achieving a more realistic representation of manual window-covering operation in simulation studies.

2.2. Daylight Performance in Office Environments

Daylight performance in office environments is assessed based on visual comfort and energy efficiency. Contemporary research highlights the importance of balancing adequate illumination, glare prevention, and the spatial distribution of daylight within interior spaces. This balance is especially important in office buildings with large glass facades, where excessive solar radiation can lead to visual discomfort and increased cooling demands (Samadi, et al., 2020).

Traditional daylight assessment methods use static indicators, such as the Daylight Factor (DF), defined as the ratio of indoor to outdoor illuminance under overcast-sky conditions. This method does not consider climate variability, solar position, or seasonal fluctuations. As a result, it is insufficient for evaluating dynamic facade systems and climate-responsive design strategies.

To overcome these limitations, climate-based daylight modeling (CBDM) has been widely implemented in building performance research. CBDM employs hourly climate data to simulate daylight conditions throughout the year, offering a realistic depiction of daylight availability under actual sky conditions. This methodology introduces performance metrics such as Daylight Autonomy (DA), Spatial Daylight Autonomy (sDA), and Useful Daylight Illumination (UDI), which are frequently used to assess daylight performance in office settings (de la Barra, et al., 2025).

Daylight Autonomy (DA) quantifies the percentage of working hours during which a specified illumination level is achieved solely through daylight. Spatial Daylight Autonomy (sDA) expands this concept by measuring the proportion of floor area that meets the illumination target for a defined portion of working hours. Useful Daylight Illumination (UDI) further refines the evaluation by categorizing illumination levels into ranges that indicate insufficient, optimal, or excessive daylight. UDI is especially useful for evaluating shading strategies because it indicates how daylight is available and used in different environmental situations. Additionally, illuminance levels above the useful range can indicate potential glare, as excessive daylight may cause visual discomfort.

Visual discomfort caused by glare remains a significant concern in office environments. Glare is typically assessed using indices such as Daylight Glare Probability (DGP), which accounts for vertical eye illuminance and luminance distribution within the visual field. However, glare perception is influenced by more than photometric factors. Experimental studies indicate that perceived indoor temperature substantially affects glare sensation, demonstrating an interaction between visual and thermal comfort domains (Garreton, Rodriguez, & Pattini, 2016). This finding highlight the necessity of integrated performance assessment when evaluating facade systems.

Daylight performance is strongly affected by facade design parameters such as window-to-wall ratio, glazing characteristics, and shading configurations. As previously discussed, shading systems are essential for regulating solar radiation, which influences daylight distribution and indoor environmental quality. Dynamic shading systems are specifically engineered to adapt to changing solar conditions, facilitating optimal use of natural light while reducing the risks of glare and overheating (Nielsen, et al., 2011; Samadi, et al., 2020).

In summary, climate-based daylight metrics offer a comprehensive framework for evaluating daylight performance in office environments. By accounting for temporal and spatial variations in daylight availability, these metrics enable the assessment of facade strategies that aim to balance visual comfort, energy efficiency, and indoor environmental quality.

2.3. Life Cycle Assessment (LCA)

As buildings become more energy-efficient in operation, the carbon emissions from the production, transportation, and disposal of building materials are becoming increasingly significant. Studies show that in high-performance buildings, where operational energy use is already low, embodied impacts can contribute a significantly larger share of total lifetime emissions (Röck, et al., 2020). This shift is particularly relevant for facade systems, where the integration of glazing, shading devices, and automation components, such as sensors and motors, creates more complex systems. Therefore, assessing operational energy alone is no longer sufficient; a perspective across the building's lifecycle is required.

Life Cycle Assessment (LCA) is a method for evaluating the environmental impact of a product throughout its life cycle, from raw material extraction to manufacturing, use, and end-of-life. LCA is defined by ISO 14040 as "the compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle." (ISO 14040:2006). LCA consists of four main phases: definition of goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation.

In the construction sector, the European standard EN 15978 provides a structured framework for applying LCA to buildings. This standard divides the life cycle into several stages: the product stage (A1–A3), which includes raw material supply, transportation, and manufacturing; the construction stage (A4–A5), which includes transportation to site and installation; the use stage (B1–B7), which includes maintenance, repair, replacement, and operational energy use; and the end-of-life stage (C1–C4), which includes demolition, transportation, waste treatment, and disposal. Module D covers potential benefits beyond the system boundary, such as recycling credits.

Environmental Product Declarations (EPDs) are calculated according to EN 15804, which defines rules for data collection, system boundaries, and reporting. One important consideration is that GWP results can vary depending on the database used. EPD data for the same building material can differ significantly across different European databases, and the dispersed and decentralized nature of EPD data makes it difficult for practitioners to access consistent information (Hoxha, et al., 2025). This is why LCA is best treated as an iterative process:

in the initial stages, a mix of generic and product-specific data sources is common, and the data selection can be gradually refined based on which inputs have the greatest impact on the results (Häfliger, et al., 2017). Despite the increasing number of published EPDs, not all building components are covered, and declarations must be updated periodically to remain valid, as also noted in EN 15804. For facade components in particular, this data gap remains a recognized challenge.

However, facade systems that incorporate dynamic, automated shading technologies are more complex. While conventional materials such as glass and shading devices are relatively well documented through EPDs, automation-related components, including motors, sensors, controllers, and communication devices, are often not fully represented in standard LCA datasets. This omission can lead to an underestimation of the environmental impacts associated with advanced facade systems.

In this context, the Product Environmental Profile (PEP) has become an important data source, particularly for electrical and electronic components used in building systems. The PEP is a standardized environmental declaration developed under the PEP ecopassport® program, providing lifecycle impact data for products such as sensors, actuators, and control systems. Like the EPD, the PEP is based on LCA methodology but is specifically tailored to electrical equipment, making it especially relevant for assessing automated facade systems. Incorporating PEP data enables a more comprehensive impact evaluation by including components typically excluded from conventional building LCA studies. Although the indicators in the PEP are worded differently from those in the EPD, they have the same meaning. The PEP indicators include global, manufacturing, distribution, installation, use, end-of-life, and module D.

Additionally, the performance of a facade system depends on its physical properties and how it functions within the building context. Material selection, glazing type, shading geometry, and automation hardware all influence the total lifecycle impact. This creates inherent trade-offs: for instance, larger glazed areas can increase daylighting but also raise embodied carbon, while automated shading can reduce energy use but introduces additional material and technological impacts. Therefore, facade design is a matter of balancing daylighting performance, energy use, and environmental impact simultaneously.

While LCA is a highly valuable tool, it presents challenges in façade studies. Data gaps are common, especially for newer technologies. Results can also be sensitive to the choice of system boundaries and the choice of background databases. Consequently, comparing findings across studies can be difficult, and uncertainty arises in LCA results for complex façade systems.

In summary, LCA provides the tools needed to evaluate not only how much energy a building saves, but also how much carbon it emits to achieve those savings. For automated shading systems, this difference is crucial. These systems can reduce operational energy use, but the additional motors, sensors, and control hardware required for automation all carry their own embodied carbon. Whether the operational savings are enough to justify these embodied carbon costs is a rarely studied question. While research in building simulation and life cycle assessment is growing, studies combining both perspectives for automated façade shading systems are still rare (Do & Chan, 2020; 2021). This study aims to fill this gap.

3. Methodology

This chapter describes the methods and tools used to evaluate the performance of the studied facade shading configurations. The chapter begins with the research approach and simulation workflow, followed by a description of the case study, building materials, and internal loads. The glazing and shading systems are then defined, along with control strategies and simulation scenarios. The chapter concludes with the methods used to assess energy performance, daylight performance, and Life Cycle Assessment, as well as the applied performance criteria.

3.1. Research Approach

This study uses a simulation-based approach to evaluate the daylight performance, energy use, thermal comfort, and life-cycle environmental impacts of various facade shading configurations applied to a reference office room. The overall workflow consists of four stages: creating an office room model, simulating performance across all scenarios, calculating life-cycle environmental impacts using LCA, and comparing the results. A visual representation of this workflow is presented in the figure below.

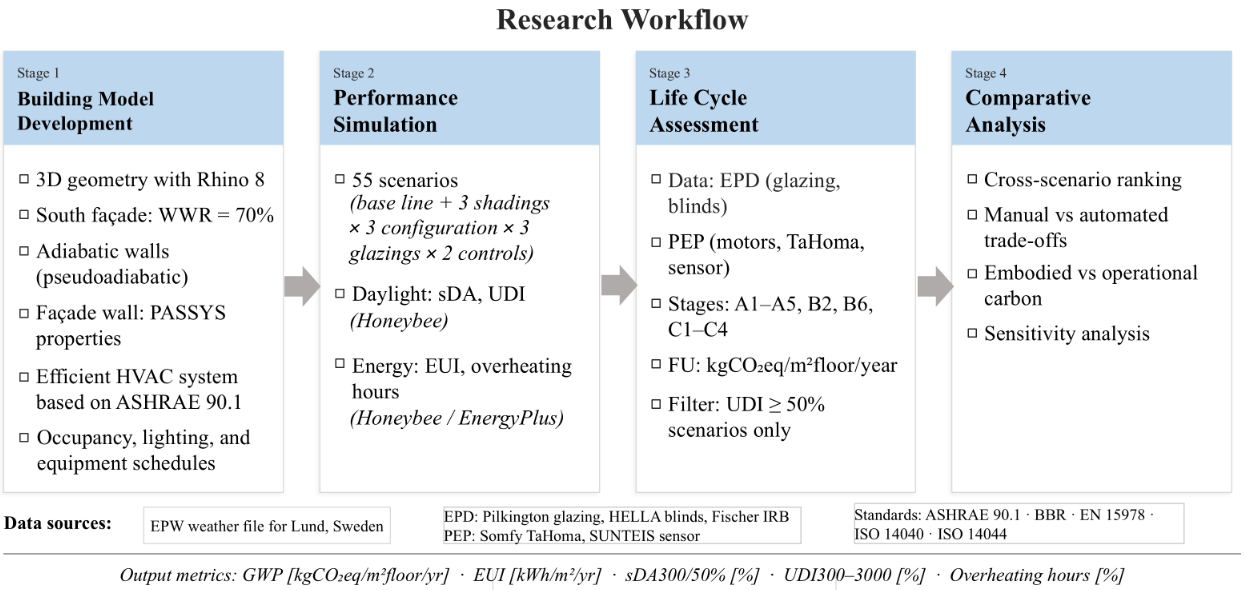

Figure 1: The research workflow consists of four stages

3.2. Simulation Tools and Workflow

The simulation process began with 3D modelling using Rhino 8 (McNeel, 2023) and Grasshopper (Davidson, 2007), an algorithmic modelling tool integrated with Rhino. Grasshopper also facilitated basic data handling and mathematical calculation on annual datasets. The following simulation software supported parametric-based modelling across various scenarios:

1. Climate data were sourced from EnergyPlus Weather files (EPW, n.d.), which represent a typical meteorological year compiled from multiple years of historical data recorded at specific local weather stations (Czachura, 2019).
2. ClimateStudio (ClimateStudio, 2024) and Honeybee (Food4Rhino, 2013) were utilized for energy and daylight simulations.
3. Grasshopper and Microsoft Excel supported energy-based Life Cycle Analysis (LCA) calculations.

The parametric modelling platform evaluates building performance across various components and configurations. The workflow is designed to analyze the influence of shading geometry, shading configurations, facade orientation, and glazing properties on building performance. The simulation workflow in this study is described in the following steps:

1. The geometry of the office space, adiabatic surfaces, and window facades was modeled to establish a baseline without shading components for comparison with parametric cases.
2. Material properties and internal loads were determined, followed by the creation of corresponding materials.
3. Schedules for occupancy, lighting, and equipment were established and implemented, as seen in the Table 16.
4. HVAC input parameters were specified.
5. The shading system, control scenarios, and shading configurations were implemented.
6. A list of parametric scenarios was created, integrating glazing and shading types, control scenarios, and shading configurations.
7. Simulations were conducted for energy performance, thermal comfort, and daylight.
8. Life Cycle Analysis (LCA) calculations were performed.

Each simulation scenario was evaluated using identical boundary conditions to ensure consistent comparisons between facade strategies.

3.3. Case Study Description

This study examined a reference office space at the EBD Laboratory at Lund University in Lund, Sweden (55.7°N, 13.2°E). The space is located in a cold climate characterized by long daylight hours in summer, short daylight periods in winter, and relatively low solar angles throughout the year. Weather data for the simulations were sourced from the EnergyPlus Weather (EPW) file for Lund, which provides hourly climate information representative of a typical meteorological year.

The simulation model in Figure 3 represents a simplified single-occupant office room based on the geometrical parameters of the EBD Laboratory test cell, including floor dimensions of 2.7 m (width) × 4.0 m (depth), ceiling height of 3.6 m, south-facing orientation, and a window-to-wall ratio of 70%. The model geometry was simplified to isolate the effect of façade configurations. This high WWR reflects the adjustable façade configuration of the EBD Laboratory test cell, which allows different fenestration scenarios to be studied under controlled conditions.

In this study, the term “fenestration system” refers to the complete assembly of the south-facing facade, consisting of glazing and shading devices. The glazing and shading types are the two elements that vary across scenarios, while all other room properties, such as geometry, orientation, internal loads, and HVAC settings, remain the same across all cases. This ensures that any differences in simulation results are due to the window configuration.

Figure 2: EBD Laboratory at Lund University, Sweden (Source: Author)

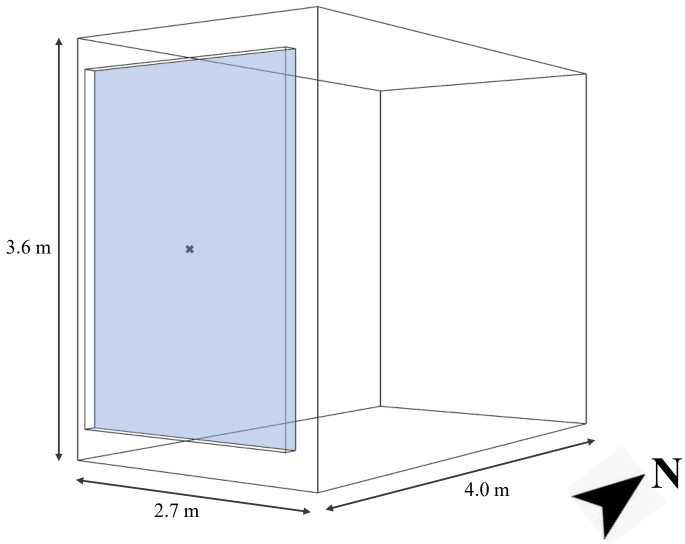

Figure 3: A simplified single-occupant office room model simulation in Rhino8

3.4. Building Materials and Internal Loads

3.4.1. Building Envelope Materials

The building envelope properties are based on the PASSYS international reference model (Wouters, et al., 1990), which was used as a reference when designing one of the office spaces in the EBD Laboratory test cells. PASSYS was adopted in this study due to the unavailability of the detailed construction data of the EBD Laboratory building. The PASSYS model provides a standardized and well-documented set of envelope properties that closely reflect the physical construction of the test cell.

The actual laboratory cell is pseudoadiabatic, meaning the surrounding zones are conditioned to match the temperature of the test room, effectively eliminating heat transfer through the opaque walls. To reflect these conditions in the simulation, all opaque surfaces except the south-facing facade, including the three surrounding walls, the roof, and the floor, were modeled as adiabatic, meaning no heat exchange occurs through them. Only the south-facing facade wall, which contains the glazing and shading system, was modeled with full thermal and optical properties, as this is the surface that varies between scenarios. This approach isolates the effect of facade configuration on the room's performance, which is the focus of this study.

Then, for the glazing system, it is determined by its thermal transmittance (U-value), solar heat gain coefficient (g-value), and visible transmittance (T-vis). The baseline glazing represents the worst-performing glazing available in ClimateStudio's default database, which is standard clear glazing with a high U-value and high solar heat gain.

Table 1. The building envelope is based on the PASSYS Test Cells standard and the baseline glazing properties from the ClimateStudio standard value

Component	Materials	Conductivity [W/m-K]	Density [kg/m^3]	Specific Heat [J/kg-K]	Thickness [m]
Roof	Concrete	1.75	2400	880	0.12
	Mineral wool	0.04	105	1800	0.25
Wall	Concrete	1.75	2400	880	0.12
	Rigid foal	0.03	30	1200	0.25
	Plywood	0.11	620	2500	0.01
Floor	Flooring	0.85	2500	653	0.01
	Cement screed	1.40	2000	1000	0.02
	Concrete	1.75	2400	880	0.12
	Mineral wool	0.04	105	1800	0.25

Component	U-Value [W/(m^{2}K)]	g-Value	T-vis
Baseline glazing	2.60	0.80	0.85

3.4.2. Internal Loads and Schedules

The internal heat gain based on Honeybee's defaults follows ASHRAE 90.1, which represents standard conditions for a typical office space. The occupancy density is set at 0.05 persons/m² with a metabolic activity level of 120 W/person (approximately 75 W of sensible heat per person), giving a total occupancy heat gain for the reference office space of approximately 40 W. The equipment load is 9.36 W/m², and the lighting power density is 7.97 W/m², both based on ASHRAE 90.1 office defaults (ANSI/ASHRAE/IES Standard 90.1-2016, 2016). The illuminance target for the lighting system is 500 lux in accordance with EN 12464-1 (SS-EN 12464-1:2021, 2021). Although the ASHRAE 90.1 value is an international standard and may be higher than the typical European office standard, it was retained as the simulation default to maintain consistency with the Honeybee tool configuration.

The occupancy, lighting, and equipment schedules follow a standard office schedule, operating from 9:00 AM to 5:00 PM on weekdays and Saturdays, with daylight saving adjustments from April to September (see Annex A). All schedules are linked to the Honeybee model.

3.4.3. HVAC System and Thermal Setpoints

The HVAC system is modelled as an ideal system using the Honeybee Ideal Air Loads component, which meets all heating and cooling requirements through conditioned supply air without modelling the system components in detail. The ventilation and HVAC parameters are set according to the Swedish Building Code (BBR) (Boverket´s mandatory provisions and general recommendations, BBR, BFS 2011:6 with amendments up to BFS 2018:4, 2018) and the Miljöbyggnad standard (Miljöbyggnad 4.0, 2022), which represents realistic performance targets for contemporary office buildings in Sweden.

In this study, all opaque surfaces except the south-facing facade were modeled as adiabatic. This resulted to all differences in heating and cooling demand between the scenarios, which are solely attributed to the fenestration system, including glazing and shading configurations. In this context, using an efficient HVAC system was the preferred choice. Because the building envelope is thermally neutral on all sides except the facade, the HVAC system responds only to the thermal load generated by the window. It also avoids introducing HVAC inefficiencies as a confounding variable, ensuring that performance differences between scenarios reflect facade behavior rather than system losses.

The ventilation system follows the BBR principle, with a constant outdoor airflow rate of 0.35 $l/s \cdot m^2$ of floor area. To meet the Miljöbyggnad bronze criteria, an additional airflow of 7 $l/s \cdot m^2$ per person is included. The ventilation system includes an enthalpy-based heat recovery unit. The heating setpoint was set to 21°C during occupied hours (Monday–Saturday, hours 7–19) with a setback temperature of 16°C during unoccupied hours. The cooling setpoint was set to 24°C during occupied hours and 29°C during unoccupied hours. These schedules were adopted from Igrexas's thesis report (Igrexas, 2024) and are detailed in Annex A (Table 16). Table 2 provides a complete summary of the HVAC parameters.

Table 2. Zone settings based on the HB IdealAir from ClimateStudio standard and ASHRAE 90.1

Settings	Value
Max Heating Supply Temperature	35 °C
Heating COP	3.50
Heating Setpoint (occupied / setback)	21 °C / 16 °C
Max Heating Capacity	Autosize
Min Cooling Supply Temperature	12 °C
Cooling COP	3.50
Cooling Setpoint (occupied / setback)	24 °C / 29 °C
Max Cooling Capacity	Autosize
Min. fresh air / person	7 l/s/p
Min. fresh air / area	0.35 $l/s/m^2$
Heat recovery type	Enthalpy
HRE Sensible	0.70
HRE Latent	0.65

3.5. Glazing and Shading System

This study evaluated three types of glazing and three types of shading. The fenestration system in each scenario consisted of one type of glazing paired with one type of shading, applied to the south-facing facade. The following sections describe each type of glazing and shading, their optical and thermal properties, and the configuration parameters used in the simulation.

3.5.1. Glazing Types

There are three types of glazing in this study, summarized in Table 3. The first is the baseline clear glass, which represents the lowest performance limit for comparison. The second is Pilkington Optifloat Clear (referred to as Float Glass), and the third is Pilkington Suncool Blue 50/27 (referred to as Coated-Float Glass). These two Pilkington products were chosen to represent the range of performance levels among commercially available glazing, from standard high-transmittance options to solar-control coated glass with much lower g-values. Their optical and thermal properties, namely U-value, g-value, visible transmittance (Tvis), and thickness, are sourced from the Pilkington Glass Range for Architects and Specifiers (Pilkington Double Glazing Units g value guide).

Table 3. Glazing by Pilkington (Pilkington Glass Range for Architects and Specifiers)

Glazing Type	Product Name	U-value [W/(m²K)]	g-value	Colour/Tint	Tvis	Thickness [mm]
Clear Glass	Base-case glass	2.60	0.80	Clear	0.85	6
Float Glass	Pilkington Optifloat Clear	1.50	0.68	Clear/neutral	0.75	6
Coated-Float Glass	Pilkington Suncool	1.00	0.28	Blue 50/27	0.60	6

3.5.2. Shading Types

Three types of shading were assessed in this study. To simplify reference throughout the thesis, each shading type is given a consistent abbreviation.

- EVB: External Venetian Blind
- ERB: External Roller Blind
- IRB: Internal Roller Blind

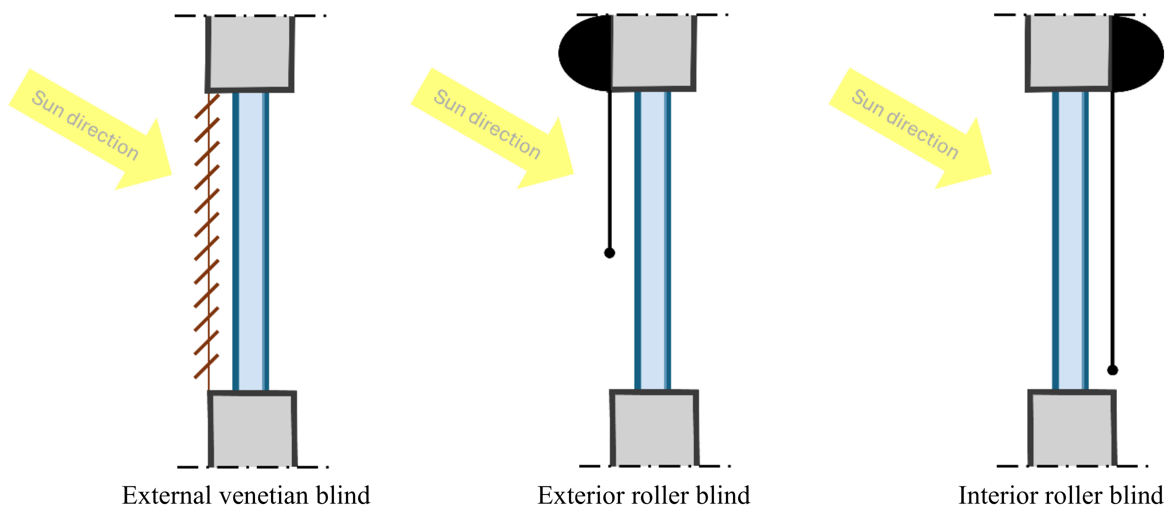

Figure 4: Shading types illustration

External Venetian Blind (EVB)

The EVB consists of aluminium-coated horizontal slats, each 80 mm wide, installed on the exterior of the façade (EPD External Venetian Blind, 2025). The slats can be tilted at different angles to control the amount of solar radiation and daylight entering the room, helping to balance between shading, transparency, and daylight utilization. By intercepting solar radiation before it reaches the glass, the EVB helps dissipate heat from the outside, making it very efficient at reducing solar heat gain. Three slat angle configurations were evaluated:

- EVB_0°: fully closed with slats standing vertical, minimum shading
- EVB_45°: partially closed slats, intermediate shading
- EVB_90°: fully open with slats lying horizontal, maximum shading

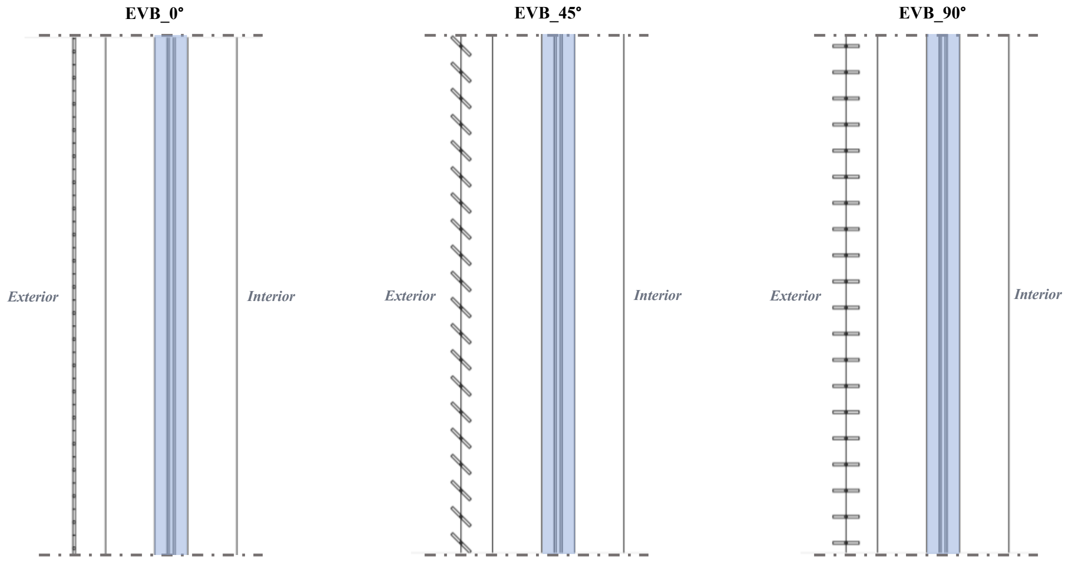

Figure 5: EVB slat angles visualization

The EVB slats are constructed from aluminum-coated metal, an opaque material that prevents direct light penetration through the surface. For this reason, the transmittance of the slats is set to 0 in the simulation. However, this does not mean the blinds create a completely closed barrier. In real life, aluminum's high surface reflectance causes sunlight hitting the slat to bounce off and enter the room. The simulation represents both effects, with light passing through the gap and bouncing between the slats, using ray-tracing calculation method. This means that even at EVB_0°, where the blind is fully closed and completely covers the window, a small amount of daylight still reaches the interior.

External Roller Blind (ERB)

The ERB consists of a PVC-coated fiberglass curtain installed on the exterior of the façade (EPD Exterior Roller Blinds, 2024). The curtain provides continuous surface coverage and can be adjusted to different levels to control how much solar radiation and daylight pass through. Depending on the fabric's transparency, the curtain can be semi-transparent, maintaining some visual connection to the outside while reducing solar heat gain. Three coverage configurations were evaluated, as follows:

- ERB_30%: 30% coverage, partially installed
- ERB_50%: 50% coverage, partially installed

- ERB_100%: 100% coverage, fully installed

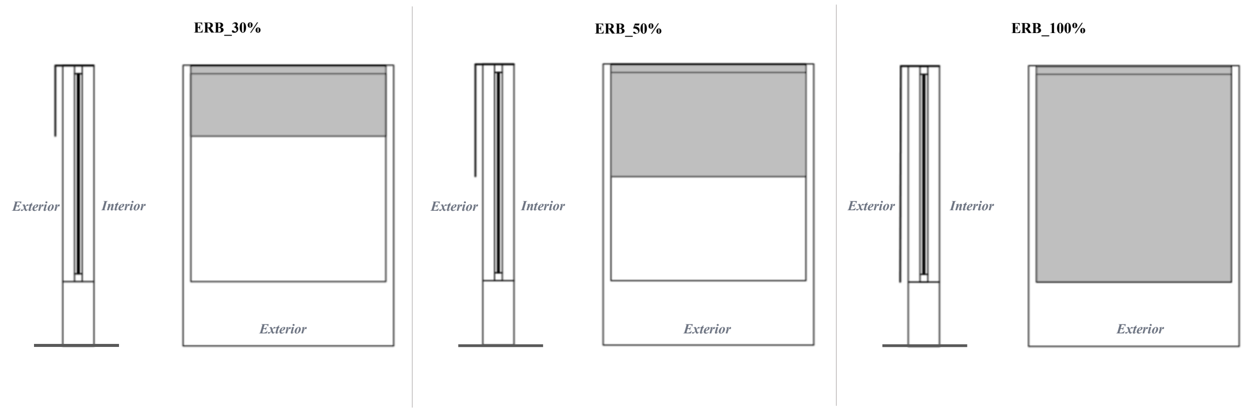

Figure 6: ERB coverages visualization

Interior Roller Blinds

The IRB is installed on the inside of the glazing (EPD Interior Roller Blind, 2023). Because of their interior position, the IRB does not block solar radiation before it reaches the glazing, but it redistributes and reduces direct sunlight within the room, thereby improving visual comfort. Three coverage configurations were evaluated.

- IRB_30%: 30% coverage, partially installed
- IRB_50%: 50% coverage, partially installed
- IRB_100%: 100% coverage, fully installed

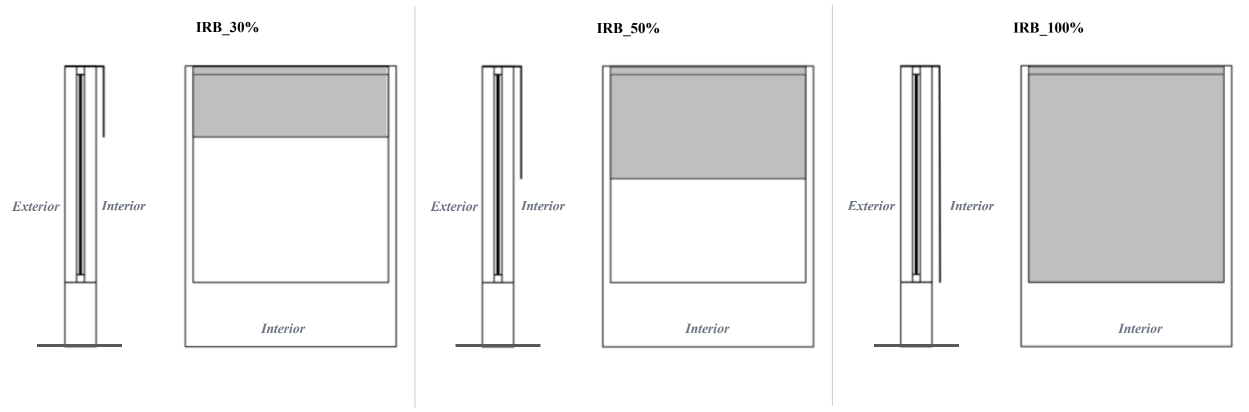

Figure 7: IRB coverages visualization

3.6. Control Strategies

Control strategies significantly affect the performance of shading systems. Two approaches are examined: manual control and automated control. These strategies are defined by user interaction and the system's responsiveness to environmental conditions (Luo, Sun, & Dong, 2020).

3.6.1. Manual Control (Occupant-Driven Behavior)

In this study, manual blind control was made dependent on occupant interaction, which is typically variable and inconsistent. Occupants do not continuously monitor and adjust the blinds, but rather, tend to react at specific moments throughout the day and then leave the blinds in the same state for extended periods (Reinhart C. F., 2004). To realistically capture this behavior, a probabilistic schedule was developed in Microsoft Excel, following the Lightswitch-2002 framework (Reinhart C. F., 2004).

3.6.1.1. The Illuminance Threshold

A work surface illumination threshold of 2 000 lux was chosen to represent conditions associated with glare risk and visual discomfort in office environments (Lolli, et al., 2019). As a first step, a baseline scenario (no shading, clear glass) was simulated to obtain hourly work-surface illumination values throughout the year. These values were then converted into a binary schedule, with 1 (blinds closed) when the illumination is equal to or exceeds 2 000 lux, and 0 (blinds open) when the illumination is below the threshold of 2 000 lux. This baseline illumination data was then exported to Microsoft Excel as reference input for developing a manual control schedule.

3.6.1.2. Decision Time Based on Occupant Behavior

Following the Lightswitch-2002 approach, occupants are assumed to notice the blinds only at specific times during the workday: when they first arrive at the office and when they return from lunch. Therefore, two daily decision-making moments are defined: 9:00 AM (the start of the workday) and 1:00 PM (after lunch). Outside these times, occupants are assumed not to adjust the blinds. This reflects the commonly observed behavior of people installing blinds once and leaving them unchanged for hours, even if outside conditions change (Reinhart C. F., 2004).

3.6.1.3. Probabilistic Response to Illuminance

Instead of fixed or static responses, occupants are modeled with probabilistic rules at each decision point. This reflects the reality that people can respond differently to the same lighting conditions. Some may tolerate glare, others may not. Some may forget to open the blinds after conditions improve. The probability values used in this study are adapted from the Lightswitch-2002 framework and represent typical occupant patterns observed in office environments (Reinhart C. F., 2004). Table 4 summarizes the rules applied at each decision-making moment.

Table 4: The assumption of the probabilistic rule response to illuminance

Condition at decision time	Rule
When illuminance is ≥ 2000 lux:	If the blind is open → 70% probability of closing
	If the blind is already closed → 90% probability of remaining closed
When illumination is < 2000 lux:	If the blind is closed → 30% probability of remaining closed
	If the blind is open → 10% probability of closing

The logic behind these values reflects actual occupant behavior patterns:

- 70%: When the room is bright and the blinds are open, most people will close them, but not everyone. Some might be busy, some tolerate the glare, and some simply do not notice.
- 90%: When the blinds are closed, people tend to leave them closed out of habit and only adjust them when there is a compelling reason.
- 30%: Even when the room is not bright, some people keep the blinds closed out of habit or for privacy.
- 10%: When the room is not bright and the blinds are open, very few people will think to close them.

The specific probability values used in this study (70%, 90%, 30%, 10%) are acknowledged as being adapted from the Lightswitch-2002 conceptual framework. Reinhart (2004) derived probabilistic switching patterns from field data in real offices, and this study follows the same conceptual structure, applying probabilities to decisions about the status of blinds at fixed times of day based on lighting conditions.

3.6.1.4. State Persistence

Once the blind state is set at the time of decision-making, it remains unchanged until the next decision-making time. The persistence rules are as follows:

- Before 9:00 AM, the blind maintains the state from the previous day (default heuristic).
- Between 9:00 AM and 1:00 PM, the state set at 9:00 AM is maintained without adjustment.
- Between 1:00 PM and 5:00 PM, the state set at 1:00 PM is maintained without adjustment.
- After 5:00 PM, the state set at 1:00 PM remains until the following morning at 9:00 AM.
- On Sundays, the blind state is always set to open (0), as the office is unoccupied.

3.6.1.5. Implementation in Excel

The probabilistic behavior is implemented in Microsoft Excel using the RAND() function, which generates a random number between 0 and 1 each time the spreadsheet recalculates. This random value is compared to a probability threshold at each decision moment to determine whether the blind state changes. The complete Excel formula applied to each occupancy hour is as follows:

=IF(F2=7,0,IF(C2<9,IF(ROW()=2,0,K1),IF(C2=9,IF(SUMIFS(D:D,B:B,B2,C:C,9)>=2000,IF(K1=1,IF(RAND()<0.9,1,0),IF(RAND()<0.7,1,0)),IF(K1=1,IF(RAND()<0.3,1,0),IF(RAND()<0.1,1,0))),IF(C2<13,K1,IF(C2=13,IF(SUMIFS(D:D,B:B,B2,C:C,13)>=2000,IF(K1=1,IF(RAND()<0.9,1,0),IF(RAND()<0.7,1,0)),IF(K1=1,IF(RAND()<0.3,1,0),IF(RAND()<0.1,1,0))), K1)))))

Where column F contains the day of the week (7 = Sunday), column C contains the hour, column D contains the hourly work surface illumination, column B contains the date, and column K contains the blind state for the previous hour. Since RAND() generates a new random value each time Excel recalculates, the schedule changes to reflect the unpredictable nature of occupant behavior. As a result, the manual schedule is not fixed, and instead represents how occupant behavior might be over the year.

3.6.2. Automated Control (Sensor-Based Strategy)

Automated control is a fully sensor-driven operation in which shading devices respond dynamically to external environmental conditions without user intervention (Derbas & Voss, 2023). In this study, the automated strategy is based on solar radiation data derived from the EPW weather file for Lund, Sweden. The shading system is activated when incident solar radiation on the south façade exceeds 120 W/m^2, triggering the closure of the shading device (Magni, et al., 2021). Furthermore, the automation supported basic shading, enabling consistent and responsive control of solar gains.

3.6.3. Comparison Between Manual and Automated Control Schedule

Figure 8 presents a side-by-side comparison of manual and automated shading control schedules over a full year. Overall, the automated schedule resulted in significantly fewer blind-closing hours, at 32.3% (2829 hours), compared to the manual schedule, which kept the blinds closed for 62.5% (5476 hours).

Figure 8: Comparison of manual and automated shading control schedules over a full year

3.6.4. Classification of Control Strategies

The distinction between manual and automated operation follows the classification established in facade system standards, such as EN 12216 (SS-EN 12216:2018). Manual systems require direct user interaction, while automated systems operate based on control logic and sensor input. Figure 9 illustrates the control strategy implemented in this study.

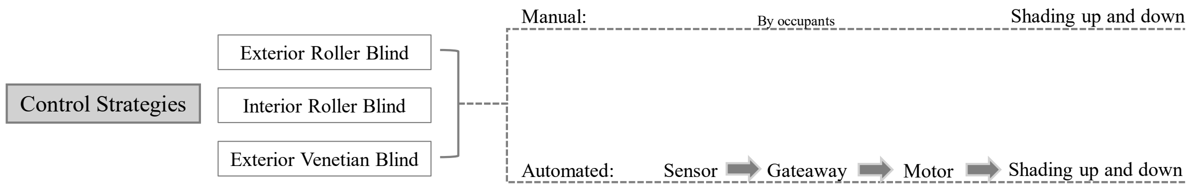

Figure 9. Control strategies for the shading system

3.6.5. Relationship Between Control Strategy and Shading Configuration

The relationship between control strategies and shading configurations in this study is one issue that needs clarification. In the simulation, each scenario is defined by a fixed shading configuration, a specific slat angle for EVBs, or a specific coverage level for ERBs and IRBs. These configurations remain unchanged throughout the simulation. The manual or automated control strategy only decides when the blinds are opened or fully pulled back. When the blinds are active, they follow the specified configuration for that scenario. When pulled back, the window is fully clear and unobstructed.

For example, in the EVB_45° scenario with automated control, the slats remain at 45° angle whenever the blinds are open. The automation does not switch between 0°, 45°, and 90°. It only decides when to open or pull back the blinds based on the solar radiation threshold. The same logic applies to the roller blind scenario; for example, in ERB_50% with manual control, the coverage is always 50% when the blinds are active.

This means that manual and automated control differ only in the timing and frequency of the blinds' operation, not in the physical arrangement of the blinds. As a result, comparing manual and automated scenarios for the same configuration directly isolates the effect of the control strategy on performance.

3.7. Simulation Scenarios

A total of 55 scenarios were simulated, including one baseline scenario with clear glass and no shading. Each scenario represents a combination of shading type (EVB, ERB, IRB), control strategy (manual and automated), glazing type (clear glass, float glass, coated float glass), and shading configuration (slat angle or coverage level). This results in 3 glazing types × 3 shading types × 3 configurations × 2 control strategies = 54 scenarios, with addition 1 baseline scenario = a total of 55 scenarios. To visualize the simulation combinations, a structured scenario tree was created in Figure 10.

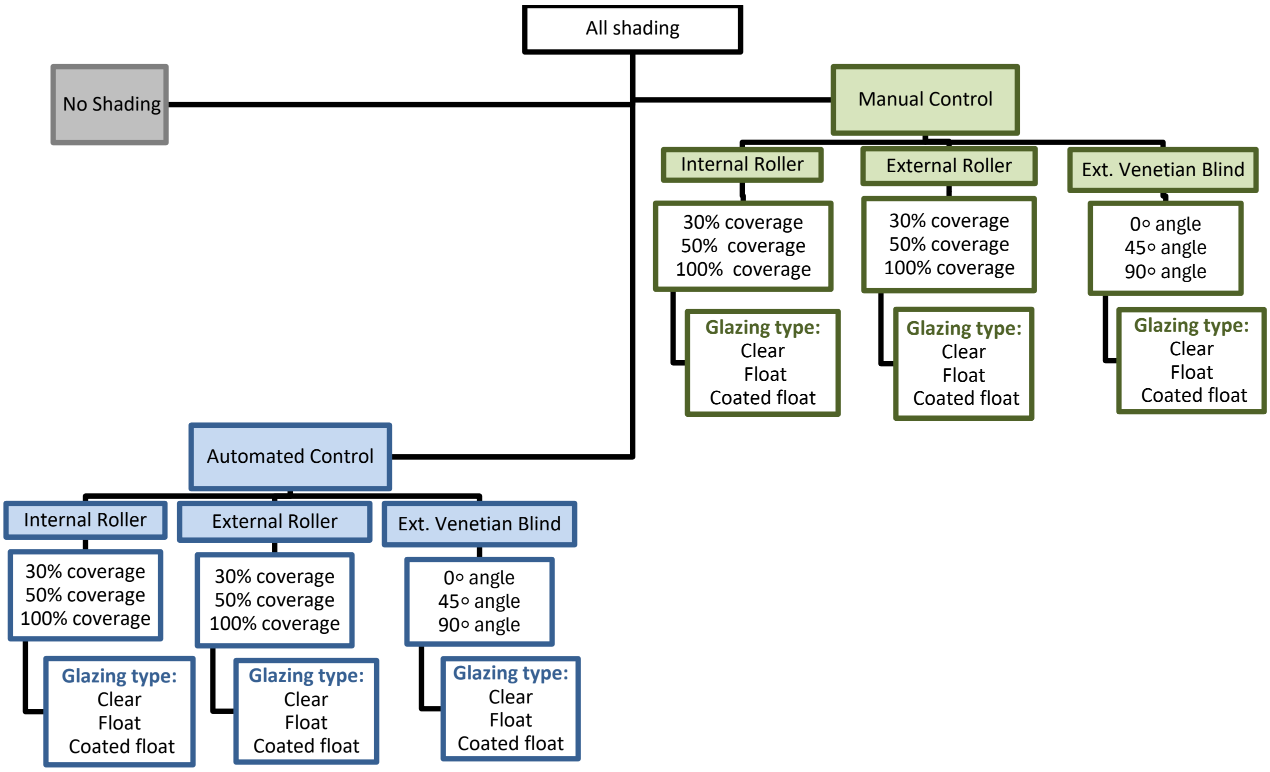

Figure 10. Scenario Tree illustrates the structure of simulation cases based on control type, shading type, and parameter variations

3.8. Energy Performance and Thermal Comfort

Energy performance and thermal comfort were assessed through dynamic building performance simulations using Honeybee for EnergyPlus (EnergyPlusTM Version 23.2.0, 2023). The simulation quantifies the Energy Use Intensity (EUI), covering annual energy demand for heating, cooling, lighting, and equipment, and evaluates indoor thermal conditions, including overheating hours. Shading operation is managed using binary (0 or 1) schedules derived from predefined thresholds, enabling dynamic responses to indoor illuminance levels for manual control and to outdoor solar radiation for automated control, which are included in Figure 8.

To represent the thermal impact of shading systems, shading devices were modeled using the EnergyPlus window-shading material framework within Honeybee. Rather than explicitly modeling shading geometry with surface-based elements, shading behavior was incorporated through modified window constructions. This approach was selected after preliminary testing showed that geometry-based shading models did not give consistent or realistic results, especially in representing solar heat gain through glazing systems (EnergyPlusTM Version 23.2.0, 2023).

For roller blinds, variations in shading coverage cannot be directly modeled due to software limitations. Consequently, the effect of partial shading is represented by adjusting the effective solar transmittance of the glazing system. This method is based on the principle that a window surface can be divided into shaded and unshaded fractions when calculating solar heat gain (Lee, et al., 2019). Within this framework, solar radiation transmitted through the window is determined by the transmittance of each portion of the surface, depending on whether it is exposed to solar radiation or covered by a shading device.

A similar concept is presented in EN ISO 52022-3:2017 (EN ISO 52022-3:2017), which provides a method for determining the solar and daylight optical properties of glazing systems combined with solar protection devices. The standard evaluates the overall performance of these systems using combined optical properties, such as total solar energy transmittance and visible transmittance, based on the characteristics of both glazing and shading materials.

Based on these principles, the effective solar transmittance is calculated as an area-weighted combination of the open and shaded portions of the window, expressed as follows:

$$Teff = (fopen \times 1.0) + (fclosed \times \tau fabric) \quad (1)$$

$fopen$ = the fraction of the glazing that remains unshaded
$fclosed$ = the fraction covered by the shading device
$\tau fabric$ = the solar transmittance of the shading material

Table 5: The result of the effective solar transmittance of all blind coverage

Roller Blind Coverage	Effective Solar Transmittance
30%	0.775
50%	0.625
100%	0.250

Thermal comfort was assessed using the overheating-hours metric, defined as the percentage of occupied time during which the indoor air temperature exceeds 26 °C. The analysis focused on the summer period from April to September, when solar gains are most significant. This metric is useful for evaluating the effectiveness of shading strategies in highly glazed office environments.

Lighting energy requirements were not obtained directly from the energy simulation outputs because the lighting system and schedules were held constant across all scenarios. Instead, lighting demand was estimated based on daylight availability, utilizing the daylight autonomy (DA) metric.

Since daylight-responsive lighting control was not explicitly modeled in the energy simulation, the required artificial lighting energy was calculated based on the target indoor illuminance level. According to the Swedish Indoor Lighting Standard (SS-EN 12464-1:2021, 2021), office spaces require an illuminance level of 500 lux. For the case study room with a floor area of 10.8 m², the total luminous flux requirement was determined by multiplying the target illuminance by the room area.

To convert luminous flux into electrical power demand, a typical luminous efficacy for modern LED systems is achieved in the range of 80–120 lm/W. In this study, a representative value of 100 lm/W was adopted (How to Benchmark LED Lighting Efficiency, 2025).

$$Lighting\ Power = \frac{space\ illuminance\ level \times floor\ area}{lighting\ luminous\ efficiency} \quad [\text{kW}] \quad (2)$$

The annual lighting energy consumption was then estimated by combining the installed lighting power with occupancy duration and daylight availability (Reinhart & Walkenhorst, 2001). This relationship is expressed as:

$$E = P \times H_{occupied} \times (1 - DA) \quad [\text{kWh/year}] \quad (3)$$

where E is the annual lighting energy demand, P is the installed lighting power, $H_{occupied}$ is the total occupied hours, and DA represents the daylight autonomy. The term $(1{-}DA)$ indicates the fraction of time during which artificial lighting is required due to insufficient daylight. Therefore, all energy requirements, including heating, cooling, equipment, and lighting, are summed to obtain the total EUI.

3.9. Daylight Performance

Daylight simulation employs climate-based daylight modelling using hourly weather data from an EPW file. The Perez-All Weather Sky Model is subsequently applied to convert the climate data into a realistic sky luminance distribution, offering a more accurate representation of actual sky conditions compared to standard CIE sky models (Reinhart & Andersen, 2006). Additional simulation parameters are provided in the table below.

Table 6: Recommended parameters for daylighting simulations (Kharvari, 2020)

Parameter	Details
Height of workplane	0.8 m
Sensor spacing	0.5 m
Illuminance set point	500 lux

The simulation was conducted using the Radiance-based daylight simulation engine through Honeybee in Grasshopper. The Radiance parameters were configured using the HB Radiance Parameter component, with the detail level set to 2 (high quality) and the ambient bounce (-ab) set to 6. This configuration tracks diffuse, indirect light for up to six consecutive reflections between interior surfaces before the simulation terminates. This approach ensures that daylight entering through a south-facing window is reflected by the floor, walls, and ceiling before reaching the sensor point inside the room. A higher ambient bounce value enhances simulation accuracy by more realistically capturing inter-surface reflections, ensuring that the daylight metric represents the actual interior light distribution.

In daylight simulations, dynamic shading behavior is modeled using opening states defined by the operational conditions of the shading device: open and closed. These states are assigned to the blind opening and controlled through schedule-based inputs, allowing the simulation to reflect the manual and automated control strategies described in the previous section.

Additionally, blind modelling in daylight simulations differs from energy simulations, where shading effects are often approximated using simplified optical properties. In daylight simulations, an explicit geometric representation of the shading device is required because indoor illumination levels depend on the spatial interaction between incoming solar radiation, shading geometry, and interior surfaces. Consequently, all shading configurations are geometrically modelled to accurately capture the penetration and distribution of daylight within space.

The material properties assigned to the simulated office space were defined using reference values from the EEBD Laboratory and representative real-world building materials. These properties are summarized in the following table.

Table 7: Modifier parameters for the office space in simulation

Opaque Material	Red Reflectance	Green Reflectance	Blue Reflectance	Specularity	Roughness
Room modifiers					
External wall	0.35	0.35	0.35	0.02	0.60
Internal wall	0.81	0.81	0.81	0.03	0.20
Ceiling	0.85	0.85	0.85	0.02	0.30
Floor	0.66	0.61	0.28	0.08	0.15

Blind modifiers					
Exterior venetian blind	0.80	0.80	0.80	0.15	0.10
Exterior roller blind	0.08	0.08	0.08	0.03	0.40
Interior roller blind	0.10	0.10	0.10	0.05	0.30

Based on these inputs, daylight simulation was simulated for all scenarios parametrically. Daylight simulation evaluated using Spatial Daylighting Autonomy (sDA300/50%) and Useful Daylighting Illumination (UDI, 300–3 000 lux). The UDI range of 300–3 000 lux follows the definition of useful daylighting from USGBC LEED v4. A UDI ≥ 50% was adopted as the minimum performance threshold.

3.10. Life Cycle Assessment (LCA)

This section presents the LCA methodology applied in this study, following the framework defined in ISO 14040, ISO 14044, and EN 15978. The assessment covers the environmental impacts of a façade shading system applied to a reference office space over a 30-year study period, expressed in Global Warming Potential ($kgCO_2eq$). The life cycle stages considered span from product manufacturing through end-of-life: the product stage (A1–A3), construction stage (A4–A5), use stage (B2 and B6), and end-of-life stage (C2–C4). Module D, which covers potential benefits from recycling and recovery beyond the system boundary, is excluded from all products to ensure consistency across scenarios.

Furthermore, structural building elements, such as walls, roofs, and floors are excluded from the LCA because they are identical across all scenarios and do not affect comparisons between façade configurations. HVAC and lighting systems are similarly excluded, aside from their operational energy use (Module B6). Small installation parts, such as brackets and fasteners, are also not included. Additionally, the window frame is excluded from the calculation and simplified, noting that the simulation compares a single glazing for the base case and triple glazing for all other scenarios.

The electricity used for building operation and automation components is assigned an emission factor of 0.115 $kgCO_2/kWh$, based on the Öresund grid mix. District heating is assigned a GWP of 0.011 $kgCO_2/kWh$, sourced from the openLCA EPD dataset. These emission factors are assumed to remain constant over the 30-year study period.

3.10.1. Functional Unit

The functional unit (FU) of this study is defined as:

"1 m² of gross floor area in a reference office space in Lund, Sweden, served by an installed fenestration system regulating daylight availability and maintaining useful illuminance within 300–3 000 lux at the office work plane for at least 50% of occupied hours, over a 30-year reference study period."

This functional unit defines the combination of the product being assessed, the fenestration system installed in the office, and the minimum performance level it must deliver. The illuminance range of 300–3 000 lux follows the USGBC LEED v4, which represents conditions that are neither too dim for work tasks nor too bright for visual comfort (USGBC, 2019). A threshold of at least 50% of occupied hours establishes the minimum acceptable performance level; the fenestration system must maintain illumination within this useful range for at least half of the office's occupancy.

Scenarios that achieve a UDI below 50% do not meet the minimum performance level specified in the functional unit. These scenarios do not provide the intended function and are therefore excluded from the LCA comparison. However, they are included in the daylight performance results to illustrate which configurations fail to meet daylight requirements.

All GWP results are expressed in $kgCO_2eq$ per m² of gross floor area per year ($kgCO_2eq/m^2floor/year$), allowing comparisons across all scenarios. The gross floor area of the reference office is 10.8 m², and the total fenestration area is 6.8 m² (WWR = 70%).

The building-scale functional unit (FU) is chosen to compare complete facade scenarios, each combining a glazing type, shading device, and control strategy. The results include the embodied carbon of all components and the building's operational energy from the energy simulation. The building geometry, floor area, building envelope, and HVAC settings remain identical across all scenarios, meaning the differences in results are solely due to the fenestration system.

Each product in this study is expressed under a different functional unit within its source EPD or PEP. The EPD for glazing expresses the impact per m² per mm of glass thickness; the EPD for blinds expresses the impact per m² of blinds; and the PEP for automation components expresses the impact per unit of product. Due to the difference in declared units across products, they cannot be directly compared without normalization. To make all products comparable under the study FU, each product's impact is scaled to the room geometry and replacement count, then divided by the gross floor area (10.8 m²) and the study period (30 years) to express it in $kgCO_2eq/m^2floor/year$. The 30-year study period was chosen based on the glazing service life reported in their EPD. Table 8 summarises the declared functional unit, service life, number of replacements, and the conversion applied for each product to align it with the study functional unit.

Table 8: The EPD/PEP declared Functional Unit (FU) and service life description from each product; then how to convert to study FU

Component	EPD/PEP declared FU	Service life [years]	Replacements in 30 years	Conversion to study FU
Float glass - Pilkington	1 m² per mm thickness	30	None	EPD value × 6 mm × 6.8 m² ÷ 10.8 m² ÷ 30 years
Coated float glass - Pilkington	1 m² per mm thickness	30	None	EPD value × 6 mm × 6.8 m² ÷ 10.8 m² ÷ 30 years
External Venetian Blind (EVB) – Schenker Storen	1 m² of blind	30	None	EPD value × 6.8 m² ÷ 10.8 m² ÷ 30 years
External Roller Blind (ERB) - SWFcontract	1 m² of blind	30	None	EPD value × 6.8 m² ÷ 10.8 m² ÷ 30 years
Interior Roller Blind (IRB) - Fischer	1 m² of blind	15	×1	EPD value × 6.8 m² × 1 ÷ 10.8 m² ÷ 30 years
Sonesse 50 Ultra Int.motor - Somfy	1 unit/15 years continuous	15	×1	EPD value × 1 ÷ 10.8 m² ÷ 30 years
LT50 Ext. motor - Somfy	1 unit/15 years continuous	15	×1	EPD value × 1 ÷ 10.8 m² ÷ 30 years
TaHoma switch - Somfy	1 unit/10 years continuous	10	×2	EPD value × 2 ÷ 10.8 m² ÷ 30 years
Sensor SUNTEIS - Somfy	1 unit/10 years continuous	10	×2	EPD value × 2 ÷ 10.8 m² ÷ 30 years

The automation components are all expressed per unit in their source PEP and have a 10- to 15-year lifetime for continuous operation. Over the 30-year study period, these components need to be replaced. Since these components are specified per unit rather than per m², their impact is normalized by dividing the gross floor area (10.8 m²) and the study duration (30 years) to express the results per m² floor/year, corresponding to the study's functional unit.

3.10.2.System Boundary

The life cycle of each facade component was assessed based on the stage structure defined in EN 15978, as summarized in Table 9. The stages considered in this study were the product stage (A1–A3), the construction stage (A4–A5), the use stage (B2 and B6), and the end-of-life stage (C2–C4). If a life-cycle stage was not specified in the source EPD or PEP, it was excluded from the calculation for that product. This is consistent with EN 15804, which allows stages to be omitted if data is unavailable, provided this is clearly reported.

Specifically, transportation and installation (A4–A5) were not stated in the Fischer EPD for Interior Roller Blinds, waste treatment (C3) was missing from the Pilkington glass EPD, and maintenance (B2) was not specified for all three blind types. If a stage is absent, it is excluded from calculations only for that product. This may lead to a slight underestimation of the absolute GWP values in this study for these products. However, since the same exclusions are consistently applied across all configurations of the same shading type, both manual and automated scenarios of each blind type are affected equally, ensuring that comparisons between scenarios remain valid.

In this study, wireless radio motors were chosen for all automation scenarios. This decision was based on two reasons: first, no Environmental Product Declaration (EPD) was available for wired products used to connect to blinds for this study. Second, wireless motors are a newer technology that is increasingly becoming the standard in building automation systems, especially as they are required for integration with smart building platforms such as the Somfy TaHoma gateway used in this study.

Since the EPDs for the three blind types do not account for the motor, additional motors were added for automation scenarios. For External Venetian Blind (EVB) and External Roller Blind (ERB), the automated scenarios use the Somfy LT50 with a standby power of 0.323 W (LT50 Motor, 2024). For the Interior Roller Blind (IRB), the automated scenarios use the Somfy Sonesse 50 Ultra with a standby power of 0.372 W (Sonesse® ULTRA 50 Motor, 2024). As this standby energy is not included in the EPD document, it is separately calculated and added to Module B6 for all automated scenarios. This method accounts for the additional energy consumption caused by the motor technology.

Table 9: Data source and system boundaries for all products that are used for LCA

Component	Data source	A1-A3	A4-A5	B2	B6	C2	C3	C4
Float Glass - Pilkington	EPD	✓	✓	✓	✓	✓	-	✓
Coated Float Glass - Pilkington	EPD	✓	✓	✓	✓	✓	-	✓
External Venetian Blind – Schenker Storen	EPD	✓	✓	-	✓	✓	✓	✓
External Roller Blind - SWFcontract	EPD	✓	✓	-	✓	✓	✓	✓
Internal Roller Blind - Fischer	EPD	✓	-	-	✓	✓	✓	✓

Component	Data source	Global	Manufacturing	Distribution	Installation	Use	End of Life

Sonesse 50 Ultra motor - Somfy	PEP	✓	✓	✓	✓	✓	✓
LT50 motor - Somfy	PEP	✓	✓	✓	✓	✓	✓
TaHoma switch - Somfy	PEP	✓	✓	✓	✓	✓	✓
Sensor SUNTEIS - Somfy	PEP	✓	✓	✓	✓	✓	✓

3.10.3.Life Cycle Inventory

According to Table 9, environmental data for glazing and shading blinds were obtained from Environmental Product Declarations (EPDs) calculated according to EN 15804. For automation components, such as the Sonesse 50 Ultra Motor, LT50 motor, TaHoma switches, and SUNTEIS sensors, data were obtained from Product Environmental Profiles (PEPs) under the ecopassport® PEP program, which follows the equivalent life-cycle principle. The use of EPDs and PEPs in a single study raises methodological concerns, as these declarations may use slightly different background databases and allocation methods. This is acknowledged as a limitation of data quality.

3.10.4.Impact Assessment

The impact assessment calculates the total GWP for each scenario by combining the contributions of all included components, after converting each product to the study's functional units. Because each EPD or PEP uses different units, the conversion is applied as follows.

For glazing, the EPD expresses impacts per m² per mm of glass thickness. The conversion to study FU (per m² of fenestration system) is:

$$GWP\ glazing = EPD\ value\ [kgCO_2eq/m^2 \cdot mm] \times thickness[mm] \times fenestration\ area\ [m^2] \div gross\ floor\ area\ [m^2]\ \div\ 30\ years \quad [\text{kgCO}_2\text{eq/m}^2\text{floor/year}] \qquad (4)$$

For shading blinds, the EPD is expressed per m² of blind, which corresponds directly to the study's FU. For blinds that need to be replaced within 30 years, the value is multiplied by the number of replacements:

$$GWP\ blind = EPD\ value\ [kgCO_2eq/m^2] \times fenestration\ area\ [m^2] \times n\_replacement \div gross\ floor\ area\ [m^2] \div 30\ years \quad [\text{kgCO}_2\text{eq/m}^2\text{floor/year}] \qquad (5)$$

For automation components expressed per unit, the PEP value per unit is multiplied by the number of replacements and divided by the total fenestration area to express it per m²:

$$n\_replacements = \frac{30}{Service\ life} \quad [\text{years}] \qquad (6)$$

$$GWP\ automation = (PEP\ value\ [kgCO_2eq/unit] \times n\_replacements) \div grossfloor\ area\ [m^2] \div 30\ years \quad [\text{kgCO}_2\text{eq/m}^2\text{floor/year}] \qquad (7)$$

3.10.5.Operational Energy Use (Module B6)

Module B6 covers two categories of energy use: building operational energy and energy use by automation components. Building operational energy, which includes heating, cooling, lighting, and equipment, is derived from energy simulation results and converted to GWP using the emission factors listed in Section 5.10:

$$GWP\ B6 = (Eheating\ [kWh/m^2/year] \times EFheating[kgCO_2/kWh]) + \big((Ecooling + Elighting + Eequipment)[kWh/m^2/year] \times EFelectricity[kgCO_2/kWh]\big) \quad [\text{kgCO}_2\text{eq/m}^2\text{floor/year}] \quad (8)$$

For the automation components, the TaHoma gateway and SUNTEIS sensors are assumed to operate continuously at their nominal power throughout the year (8 760 hours/year):

$$E\ automation = P\ active\ [W] \times 8\,760\ [h/year] \quad [\text{Wh/year}] \quad (9)$$

The motor operates in two states, namely standby (low power, continuous) and active (higher power, during the shading adjustment movement, which lasts about one minute per action):

$$E\ automation = (P\ standby\ [W]\ \times t\ standby\ [h]) + (P\ active\ [W] \times t\ operation\ [h]) \quad [\text{Wh/year}] \quad (10)$$

For the Somfy radio motors, the B6 operational energy is calculated directly from the motor power specifications provided in the Somfy product documentation. The motors operate in two states: standby mode and active mode. The exterior Somfy motor draws 0.323 W in standby and 90 W during active operation. The interior Somfy motor draws 0.372 W in standby and 114 W during active operation. Using the annual cycle count of 2 829 cycles from the automated schedule simulation.

All automation energy was converted to GWP using the electrical emission factor:

$$GWP\ B6\ automation = E\ automation\ [kWh/year] \times EFelectricity[kgCO_2/kWh] \div gross\ floor\ area\ [m^2] \quad [\text{kgCO}_2\text{-eq/m}^2\text{floor/year}] \quad (11)$$

3.10.6.Total Impact Assessment

The total Global Warming Potential (GWP) per m² of fenestration system was determined for each facade configuration defined in the parametric study. Each case represents a unique combination of shading type, control strategy, and system configuration. The total environmental impact for each case was calculated as follows:

Baseline: $GWP\ total = GWP\ B6$ [kgCO$_2$-eq/m²floor/year] (12)

Manual cases: $GWP\ total = GWP\ glazing + GWP\ blind + GWP\ B6$ [kgCO$_2$-eq/m²floor/year] (13)

Automated cases: $GWP\ total = GWP\ glazing + GWP\ blind + GWP\ TaHoma + GWP\ sensor + GWP\ B6 + GWP\ B6\ automation$ [kgCO$_2$-eq/m²floor/year] (14)

3.10.7. Sensitivity Analysis

A sensitivity analysis assessed the robustness of the LCA results and scenario rankings to data uncertainty for automation components. Because PEP data for the motors, TaHoma gateway and SUNTEIS sensors carry greater uncertainty than EPD data for established construction products, three alternative scenarios were tested and compared to the base case:

- Scenario S1 with reduced automation impacts: GWP values for all automation components are reduced by 20% across all life cycle stages. This tests whether scenario rankings remain stable if the automation hardware has a lower environmental impact
- Scenario S2 with increased embodied impacts: GWP values for all automation components are increased by 20%, but only applied to the production stages: manufacturing, distribution, and installation. This is more targeted than an increase across all stages, as production stage data carries the greatest uncertainty in PEP and is the stage most likely to vary across manufacturers.
- Scenario S3 using alternative PEP data: An alternative PEP data set is applied to motor components, replacing the base case data source. This tests the sensitivity of the results to the chosen data source.

For each scenario within the range based on the functional unit, the total GWP is recalculated, and the resulting ranking is compared to the baseline scenario. Scenarios in which ranking remains constant across all three sensitivity scenarios are considered robust to data uncertainty. Configurations in which ranking changes are considered sensitive, and the reasons for this sensitivity are discussed in the discussion.

3.11. Performance Criteria and Target Values

To evaluate the performance of fenestration systems, a set of quantitative performance criteria and target values is defined based on established standards and certification frameworks, including LEED v4, Passive House, and Miljöbyggnad. These criteria provide reference thresholds for assessing daylight availability, visual comfort, thermal conditions, energy performance, and environmental impact.

Table 10. Performance Criteria and Target Values

Category	Indicator	Description	Target/Benchmark	Source
Energy	Heating demand	Annual heating energy	≤ 70 × Fgeo = bronze	Miljöbyggnad (Miljöbyggnad 4.0, 2022)
	Annual energy use	Annual delivered energy	≤ 200 Bq/m³ = bronze Measured energy use must include heating, cooling, equipment, lighting.	Miljöbyggnad (Miljöbyggnad 4.0, 2022)
Thermal comfort	Overheating hours	Percentage of time indoor temperature > 25°C	≤ 10% annually	Passive House (Passive House, 2016)
Daylight	sDA300/50%	Percentage of floor area receiving ≥300 lux for at least 50% of occupied hours	≥ 55% (minimum), ≥ 75% (good)	USGBC LEED v4 (USGBC, 2019)
	UDI	Fraction of time illuminance is within 300–3 000 lux	≥ 50% of occupied area	USGBC LEED v4 (USGBC, 2019)
LCA	GWP	Global warming potential over life cycle	Reported across modules A–C	Miljöbyggnad (Miljöbyggnad 4.0, 2022)

4. Results

This chapter presents the results of all simulations and LCA calculations for all 55 scenarios. Scenarios with a UDI below 50% are excluded from the LCA comparisons based on the functional unit (FU) definition. These scenarios are marked (✗) and is only maintained in daylight performance results.

The results of the study are organised into three main categories: energy and thermal comfort, daylight, and environmental impact based on LCA calculation.

4.1. Energy Performance and Thermal Comfort

The baseline condition serves as the reference point for all comparisons. This condition represents the initial conditions before any shading interventions were implemented. This baseline condition achieved an EUI of 139.5 kWh/m^2/year, with cooling dominating at 49.7 kWh/m^2/year compared to heating at 18.3 kWh/m^2/year. Overheating at 47.8% of occupancy hours, nearly five times at the Passive House threshold of 10%, and peak cooling loads reached 258.4 W/m^2, this shows the extreme thermal challenges by no-shading, south-facing 70% WWR window. Despite high daylight availability (sDA = 100%), the UDI was only 30.9%, failing to meet the functional unit requirement. All shading scenarios were evaluated against this baseline.

4.1.1. Heating and Cooling Demand

Figure 11 and
Figure 12 present the annual heating and cooling demand for all scenarios with manual and automated control, respectively, categorized by glass type. Respectively, these show both values side by side for each shading configuration and glazing type. Then, Figure 13 shows the average heating and cooling demand under different shading control strategies, using the average values as a direct comparison between manual and automated across all shading types.

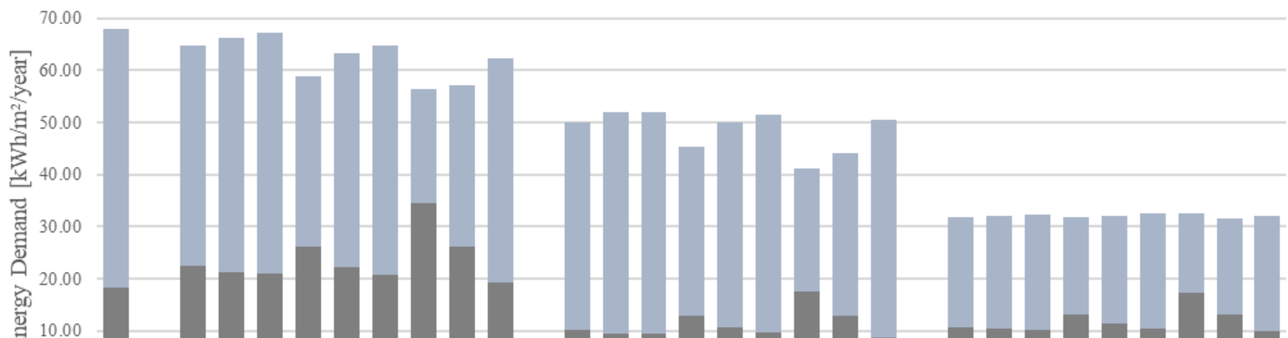

Figure 11: Comparison of heating and cooling energy demand for manual control

Figure 11 above compares heating and cooling demand for manual shading scenarios. In general, clear glass shows the highest total energy demand, followed by float glass and coated float glass.

For the IRB scenarios, the cooling demand under the clear glass ranges between 42.1 kWh/m² and 46.2 kWh/m², while for the float glass it has a lower demand between 39.3 kWh/m² and 42.7 kWh/m². With coated float glass the cooling demand decreased more into around 20.8 kWh/m² to 22 kWh/m². On the other hand, the heating demand shows the opposite trend where coated float glass has slightly higher energy demand with a range of 10.2 kWh/m² to 10.5 kWh/m² compared to float glass with a lower range of 9.34 kWh/m² to 10.1 kWh/m².

For the ERB scenarios, the lowest cooling demand is generally achieved at 100% coverage. Under the clear glass, ERB 100% has 32.8 kWh/m² cooling demand, compared to 41.2 kWh/m² at 50% coverage and 44.1 kWh/m² at 30% coverage. The same pattern is seen for float glass and coated float glass. The opposite trend is observed for heating demand, which increases with coverage. Under the float glass, where heating demand increases from 9.78 kWh/m² at 30% coverage to 10.6 kWh/m² at 50% coverage and 12.9 kWh/m² at 100% coverage. For the coated float glass, the heating demand increases from 10.4 kWh/m² at 30% coverage to 11.2 kWh/m² at 50% coverage and 13.1 kWh/m² at 100% coverage.

The EVB scenarios show a similar pattern, with cooling demand generally rising as the blind angle opens. For clear glass, EVB at 0° (fully closed) results in the lowest cooling demand of 21.9 kWh/m², increasing to 31.1 kWh/m² at 45° and 43.1 kWh/m² at 90°. For float glass, the cooling demand varies from 23.5 to 41.6 kWh/m² depending on the blind angle. Coated float glass consistently shows lower cooling demand, ranging from 15.3 kWh/m² to 22.31 kWh/m². Regarding heating demand, lower cooling demand often correlates with higher heating values. Under clear glass, EVB 0° has a heating demand of 34.4 kWh/m², decreasing to 19.1 kWh/m² at 90°. For float glass, EVB 0° is 17.6 kWh/m², dropping to 8.78 kWh/m² at 90°, and coated float glass has 17.2 kWh/m² at 90°, reducing to 9.92 kWh/m² at 90°.

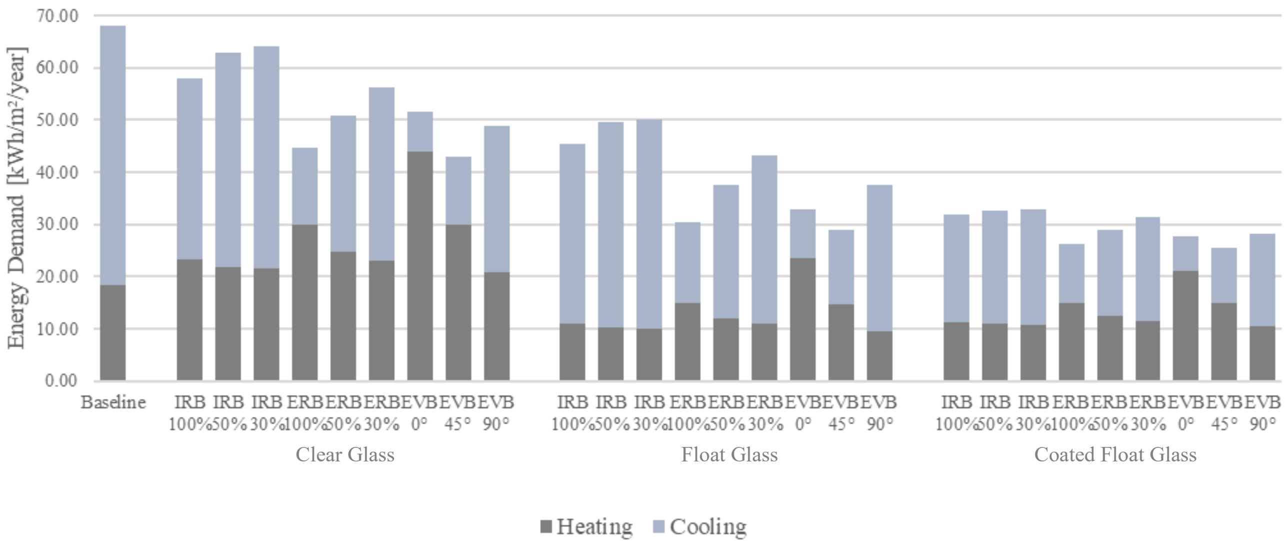

Figure 12: Comparison of heating and cooling demand for automated control

The automated shading control shown in
Figure 12, demonstrates similar performance patterns to the manual cases, although it generally results in lower cooling demand across most configurations.

For the automated IRB scenarios, the cooling demand with clear glass varies from 34.5 kWh/m² to 42.6 kWh/m², and the heating demand ranges from 21.5 kWh/m² to 23.2 kWh/m². In float glass, cooling demand ranges from 25.5 kWh/m² to 43.6 kWh/m², with heating demand values between 10.9 kWh/m² and 14.8 kWh/m². Coated float glass shows lower cooling demand, ranging from 21.4 kWh/m² to 22.8 kWh/m², and heating demand from 10.7 kWh/m² to 15.0 kWh/m².

Automated ERB scenarios generally show lower cooling demand than IRB. Under clear glass, cooling demand rises from 14.7 kWh/m² at 100% coverage to 25.9 kWh/m² at 50%, and reaches 33.1 kWh/m² at 30% coverage. Heating demand decreases from 29.9 kWh/m² to 20.5 kWh/m² as coverage reduces. Similar trends are seen with float glass, with cooling demands between 10.9 kWh/m² and 19.0 kWh/m², and with coated float glass, which ranges from 8.4 kWh/m² to 17.7 kWh/m².

For automated EVB scenarios, the lowest cooling demand occurs at 0°, while larger blind angles result in higher cooling demands. Under clear glass, EVB at 0° records a cooling demand of 7.6 kWh/m² and a heating demand of 44.0 kWh/m². At 45°, the cooling demand rises to 13.2 kWh/m², and at 90°, it reaches 28.1 kWh/m². Similar patterns are seen with float glass and coated float glass. For float glass, the cooling demand increases from 9.4 kWh/m² at 0° to 14.6 kWh/m² at 45°, and to 29.1 kWh/m² at 90°. In coated float glass, the cooling demand varies from 6.8 kWh/m² to 10.7 kWh/m² and 17.7 kWh/m² respectively.

Across all glazing types, the automated ERB and EVB scenarios generally achieve lower cooling demand compared to the automated IRB scenarios. However, this reduction in cooling demand is often accompanied by higher heating demand values, especially in the EVB 0° configurations.

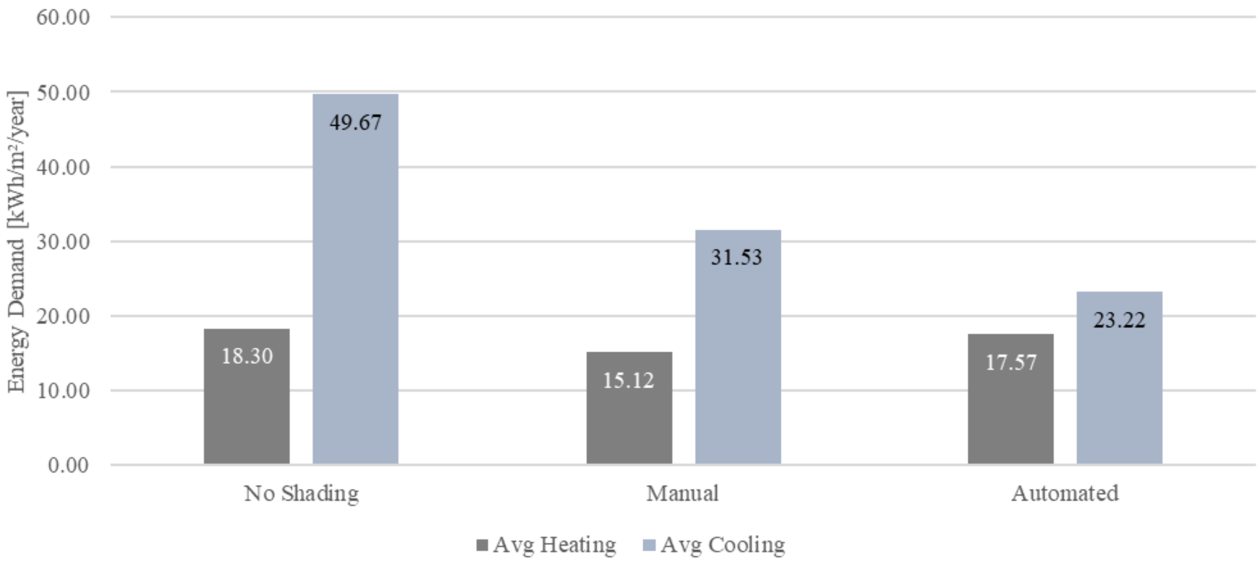

Figure 13: Average heating and cooling demand under different control strategies

To provide an overall comparison of the baseline, manual, and automated shading scenarios, Figure 13 presents the average heating and cooling demands across all simulated cases. It summarizes the overall performance of each control strategy by combining the results from all glazing types and shading configurations.

Figure 13 illustrates that both manual and automated shading controls reduce the average cooling demand compared to the no-shading baseline scenario. The baseline shows an average cooling demand of 49.67 kWh/m², while manual shading reduces this to 31.53 kWh/m², representing a reduction of around 36.5%. Automated shading further reduces the cooling demand to 23.22 kWh/m², achieving an overall reduction of approximately 53.3% from the baseline.

For heating demand, the baseline case records an average of 18.30 kWh/m². The manual scenarios show the lowest average heating demand at 15.12 kWh/m², representing a reduction of approximately 17.4% from the baseline. The automated scenarios show an average heating demand of 17.57 kWh/m², which is a smaller reduction of approximately 4% compared to the baseline.

Overall, the automated shading scenarios achieve the largest reduction in average cooling demand, while the differences in heating demand remain relatively small across the control strategies.

The peak heating and cooling load values obtained from the simulations are used to illustrate the implications for HVAC system design. Peak heating loads across all scenarios ranged from 64.5 W/m² to 86.2 W/m², primarily influenced by glazing type. Coated float glass consistently achieved the lowest peak heating loads (64.5 W/m² to 67.6 W/m²) due to its lower U-value, while clear glass shows the highest peak heating loads (83.4 W/m² to 86.2 W/m²), regardless of shading type. This range indicates that peak heating loads are driven by the thermal properties of the building envelope rather than shading operation.

Peak cooling loads show a much wider range, from 24.3 W/m² (EVB_0° with coated float glass) to 258.4 W/m² (baseline with no shading). This large difference in peak cooling load illustrates the important role that shading and glazing types play in determining HVAC sizing requirements. A building relying on interior roller blinds with clear glass requires a much larger HVAC system than one using external venetian blinds with coated float glass. Table 11 presents the peak heating and cooling values for the selected scenarios. The baseline serves as a reference point.

Table 11: Peak heating and cooling for the selected scenarios

Configuration	Control	Glazing type	Peak heating [W/m^2]	Peak cooling [W/m^2]
Baseline (no-shading)	-	Clear	86.2	258.4
IRB_100%	Manual	Clear	83.4	208.9
IRB_50%	Manual	Coated float	64.5	116.2
IRB_100%	Auto	Clear	85.6	208.5
ERB_100%	Manual	Clear	85.6	72.1
ERB_50%	Manual	Clear	85.6	125.2
ERB_50%	Auto	Coated float	67.5	68.3
EVB_45°	Manual	Clear	85.7	62.4
EVB_45°	Auto	Clear	86.1	61.9
EVB_45°	Auto	Coated float	67.5	42.0

IRB_100%, both manual and automated, with clear glass, indicates the worst shading performance at full coverage. IRB_50% with coated float glass represents the best IRB combination. ERB_100% and ERB_50% with clear glass demonstrate the coverage effect of external roller blinds, while ERB_50% automated with coated float glass is the best ERB scenario. EVB_45°, manually operated with clear glass, serves as a baseline for EVB performance, with its equivalent automated scenarios enabling direct comparison. Finally, EVB_45° automated with coated float glass is identified as the best overall scenario in the study.

4.1.2. Total Energy Use Intensity (EUI)

The total energy use intensity (EUI) represents the sum of heating, cooling, lighting, and electrical equipment demand. It provides an overall indicator of the building's energy performance.

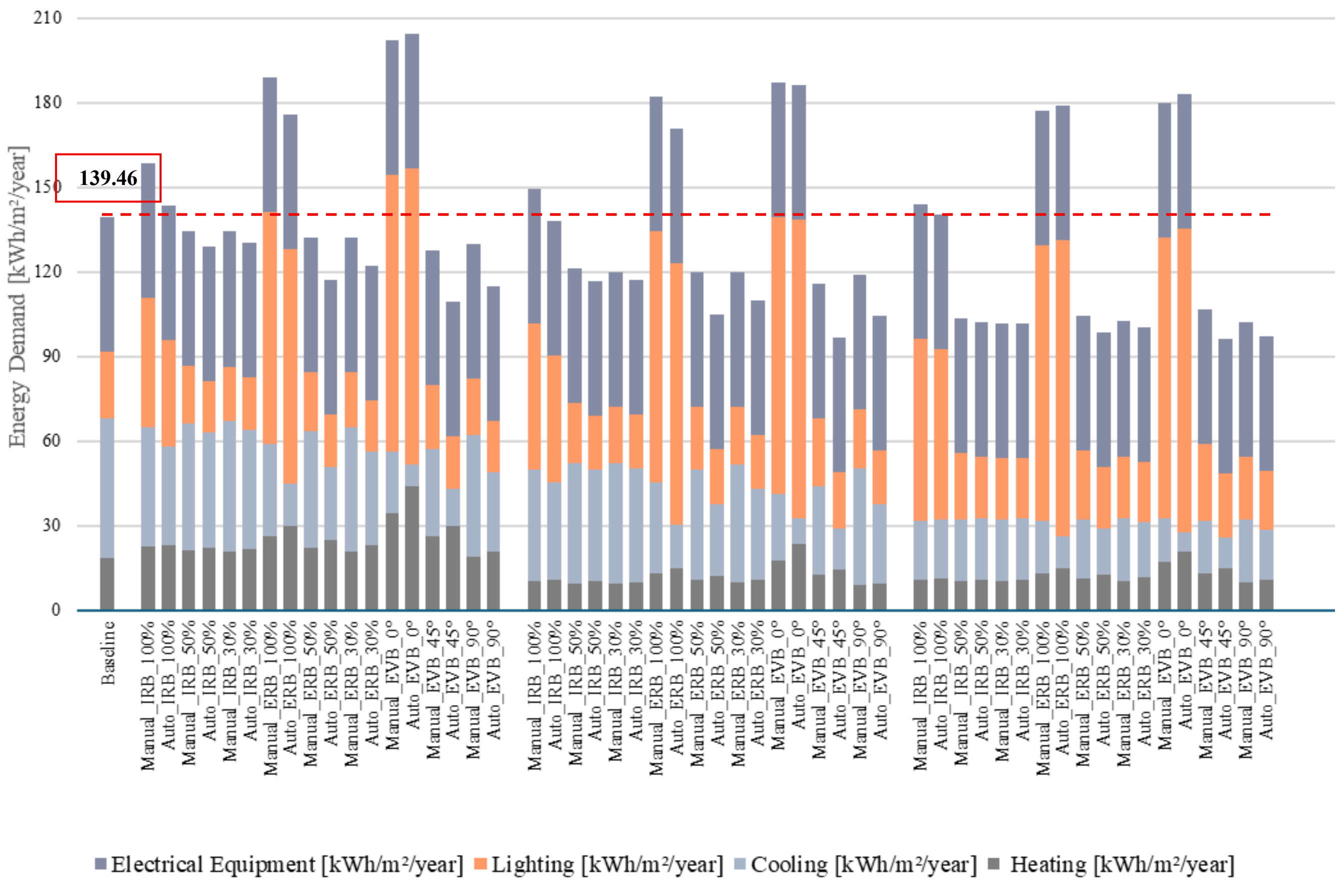

Figure 14. Total Energy Use Intensity (EUI) comparison for all scenarios

Figure 14 presents the EUI results for all scenarios, comparing manual and automated shading control across different glazing types and shading configurations. The no-shading baseline has an EUI of 139.46 kWh/m2/year, which is indicated by the dashed horizontal line. This serves as a reference point for evaluating the performance of all other cases.

In general, most shading scenarios reduce the EUI compared to the baseline. However, the EUI results also show that the total energy use is influenced differently by heating, cooling, lighting, and equipment demand depending on the shading configuration.

The results show that lighting demand contributes significantly to total EUI across many scenarios. In several cases, reductions in cooling demand are accompanied by increases in lighting demand due to reduced daylight penetration caused by the shading systems. This can be observed especially in scenarios with higher shading coverage or more closed venetian blind angles.

A clearer pattern can be observed when comparing the different shading configurations. For roller blinds, 50% coverage generally achieves lower EUI values compared to both 30% and 100% coverage. Similarly, for venetian blinds, the 45° angle consistently results in lower EUI values compared to the 0° (closed) and 90° (fully open) positions.

The stacked EUI graph shows that these differences are mainly related to the balance between cooling and lighting demand. At lower shading levels, such as 30% coverage or fully open (90°) venetian blinds, more solar radiation enters the space, which increases cooling demand. In contrast, higher shading levels, such as 100% coverage or 0° venetian blind angles, reduce cooling demand but increase lighting demand because less daylight enters the room. Intermediate shading configurations, such as 50% roller coverage and 45° venetian blind angles, show a more balanced distribution between cooling and lighting energy use, resulting in lower overall EUI values.

The equipment demand remains constant across all scenarios at approximately 47.75 kWh/m², while variations in total EUI are mainly driven by changes in heating, cooling, and especially lighting demand. This indicates that the shading configuration affects not only thermal performance but also daylight availability, which consequently influences artificial lighting energy consumption.

4.1.3. Thermal comfort with Overheating Hours

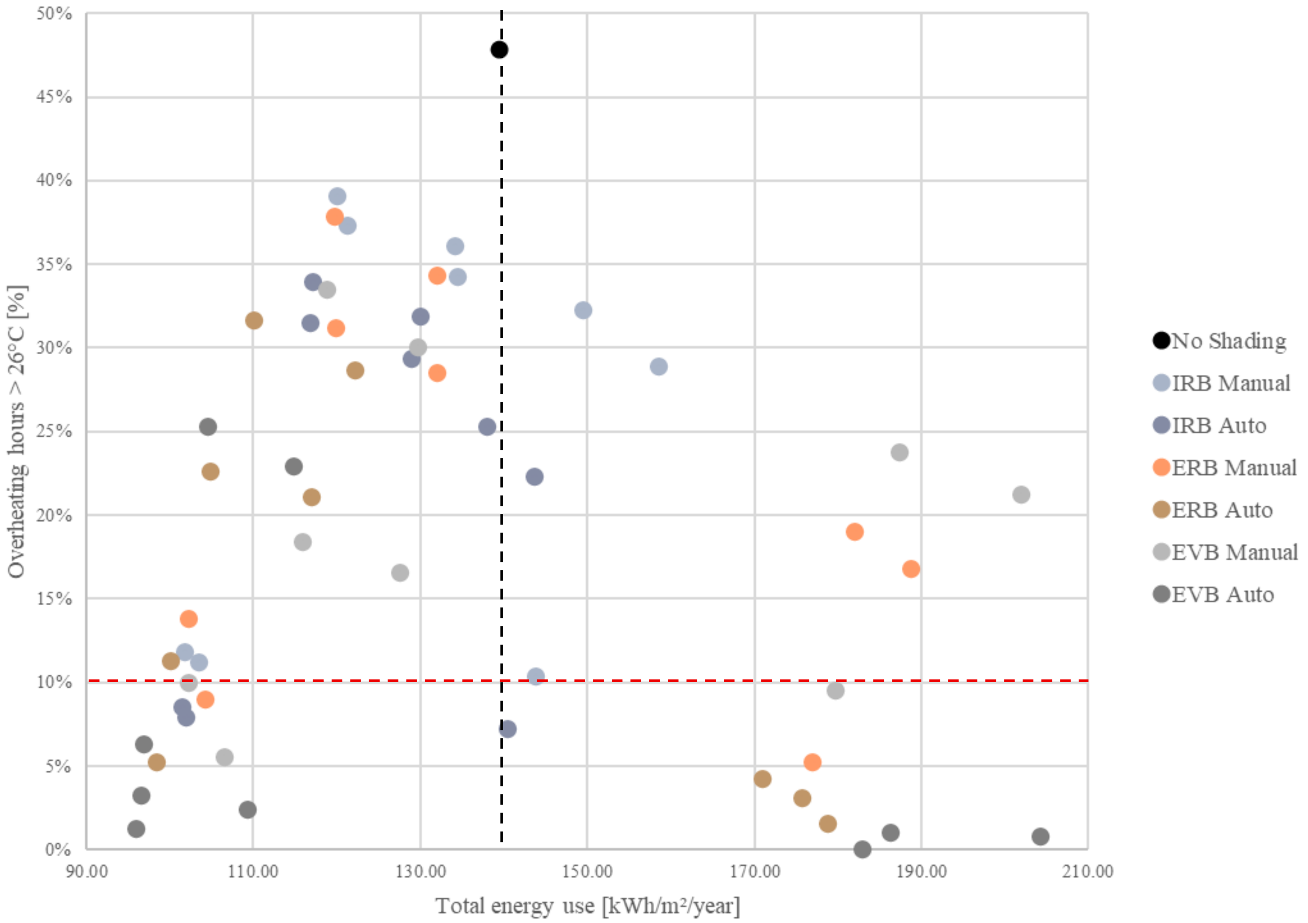

Figure 15: Overheating hours compared to EUI for all scenarios

Figure 15 shows the relationship between EUI and overheating hours above 26 °C across all shading scenarios. This allows an evaluation of the trade-off between energy efficiency and thermal comfort. For the baseline, it has the worst result with 47.81% overheating hours, indicating that without solar control, the office interior frequently exceeds the acceptable temperature threshold.

The red line indicates the 10% overheating threshold, while the vertical dashed line represents the baseline EUI for the no-shading case. Based on these two reference lines, the graph can be divided into four quadrants. The lower-left area represents the most desirable performance, where both EUI and overheating hours are low. In contrast, the upper-right quadrant shows poor performance in both aspects, with high energy use and high overheating. The upper-left quadrant indicates cases with lower energy use, but high overheating, while the lower-right area represents cases with good thermal comfort but higher energy consumption.

Out of all simulated scenarios, 19 cases achieve overheating below the threshold. Among these, 16 cases are external shading systems, while only 3 cases from internal roller blind (IRB). Around 74% of the acceptable thresholds are under automated control, while the rest are manual shading cases. This indicates that external shading systems are generally more effective in controlling overheating compared to internal shading systems.

Among all shading configurations, automated EVB demonstrates the most consistent performance in balancing overheating and EUI. Seven out of eight automated EVB scenarios are within the acceptable range. The EVB scenarios with 45° and 90° slat angles generally achieve low overheating hours and lower EUI values, especially for coated float glazing, where EUI values are around 96-97 kWh/m²/year. Although the fully closed EVB at 0° with the same glazing achieves close to 0% overheating, it has a significantly higher EUI of around 183 kWh/m²/year. It indicates that while EVB at 0° effectively reduces overheating, it also increases energy consumption.

Generally, external shading systems are more effective at reducing overheating than internal shading systems. External roller blinds shows better thermal comfort under automated control for coated float glass, where overheating hours achieve below 10%. However, several manual ERB scenarios with clear and float glazing still exceed acceptable limits. Internal roller blinds, whether manual or automated, mostly cluster in the upper-middle of the graph, particularly for clear and float glazing types, indicating higher overheating hours of 20-40%, despite relatively low EUI. This emphasizes that a reduction in overall energy use does not always result in better thermal comfort.

To further evaluate the relationship between daylight quality and thermal comfort, Figure 16 presents the UDI versus overheating hours for all scenarios. This scatter plot allows scenarios to be assessed simultaneously against both a daylight quality threshold (UDI ≥ 50%, marked by the vertical dashed line) and the thermal comfort threshold (overheating ≤ 10%, marked by the horizontal red dashed line). Scenarios positioned in the lower-right quadrant with high UDI and low overheating, which represent the most balanced performance in terms of both daylight quality and thermal comfort.

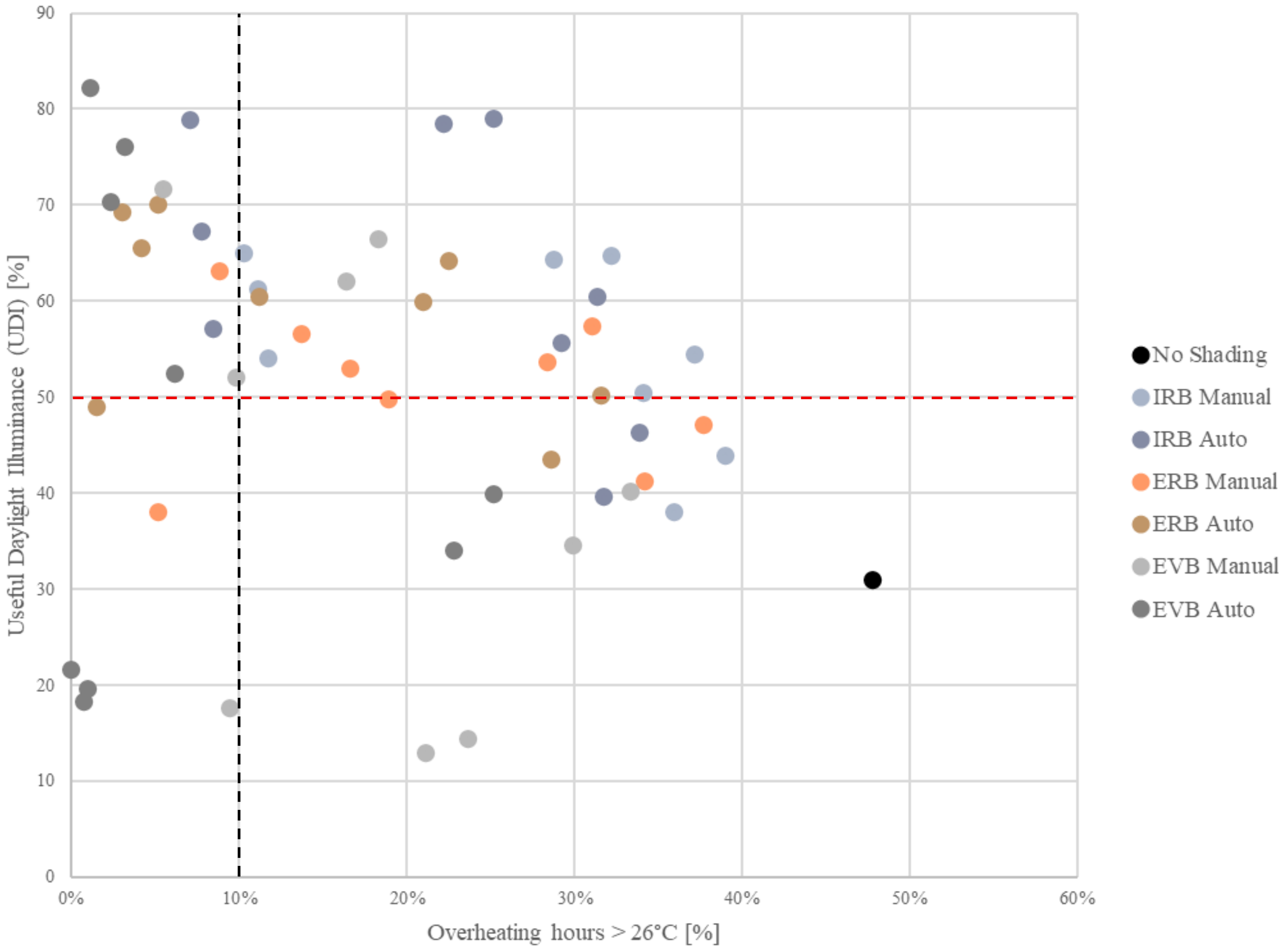

Figure 16: UDI versus overheating hours (>26°C) for all shading scenarios and control strategies

Based on the Figure above, all automated EVB_45° and ERB_50° scenarios with coated float glass meet the Passive House benchmark of ≤ 10%, while the baseline significantly exceeds it at 47.8%. The best result is the automated EVB_45° with coated float glass, with only 1.2% overheating hours.

The interior roller blind configuration was largely ineffective in reducing overheating. Even the manual IRB_100% with clear glass showed 28.8% overheating, representing only a slight improvement over the baseline. This is because the IRB is positioned inside the glass, where solar radiation has already passed through the glass and converted to heat before the blinds intercept it. For thermal comfort management in south-facing offices with high WWR, external shading is a crucial option.

The scatterplot in Figure 16 illustrates a clear trade-off where configurations with aggressive shading (bottom left: low overheating, low UDI) tend to fail to meet the functional unit, while configurations with minimal shading (top right: high UDI, high overheating) fail to meet the thermal comfort target. The ideal configuration is in the bottom-right region, high UDI with low overheating, and this is mostly the EVB_45° and ERB_50° automated scenarios with coated float glass.

4.2. Daylight performance

Daylight performance is evaluated using two metrics: spatial Daylight Autonomy (sDA) and Useful Daylight Illuminance (UDI). sDA measures the percentage of the floor area that receives at least 300 lux for at least 55% of occupied hours, while UDI captures the fraction of occupied hours during which illuminance falls within the useful range of 100-3 000 lux, with at least 50%. Together, these metrics allow an assessment of both daylight sufficiency and excess across the different shading scenarios. Figure 17 presents an overview of sDA and UDI for all shading types and control strategies, illustrating configurations that differ from the no-shading baseline.

4.2.1. Baseline Daylight Performance

The no-shading baseline achieved an sDA of 100%, meaning the entire floor received sufficient daylight throughout the year. However, the UDI was only 30.9%, which is below the 50% threshold. This indicates that during working hours, the work plane illuminance exceeds 3 000 lux, pointing to a persistent risk of over-illumination glare. Consequently, despite achieving excellent spatial daylight coverage, the baseline scenario failed to meet the functional unit requirements. These findings emphasize that a high sDA does not guarantee beneficial daylight quality.

4.2.2. Shading Type and Configuration Daylight Performance

Figure 17 presents sDA and UDI for all scenarios, enabling comparison across shading types, configurations, glazing types, and control strategies.

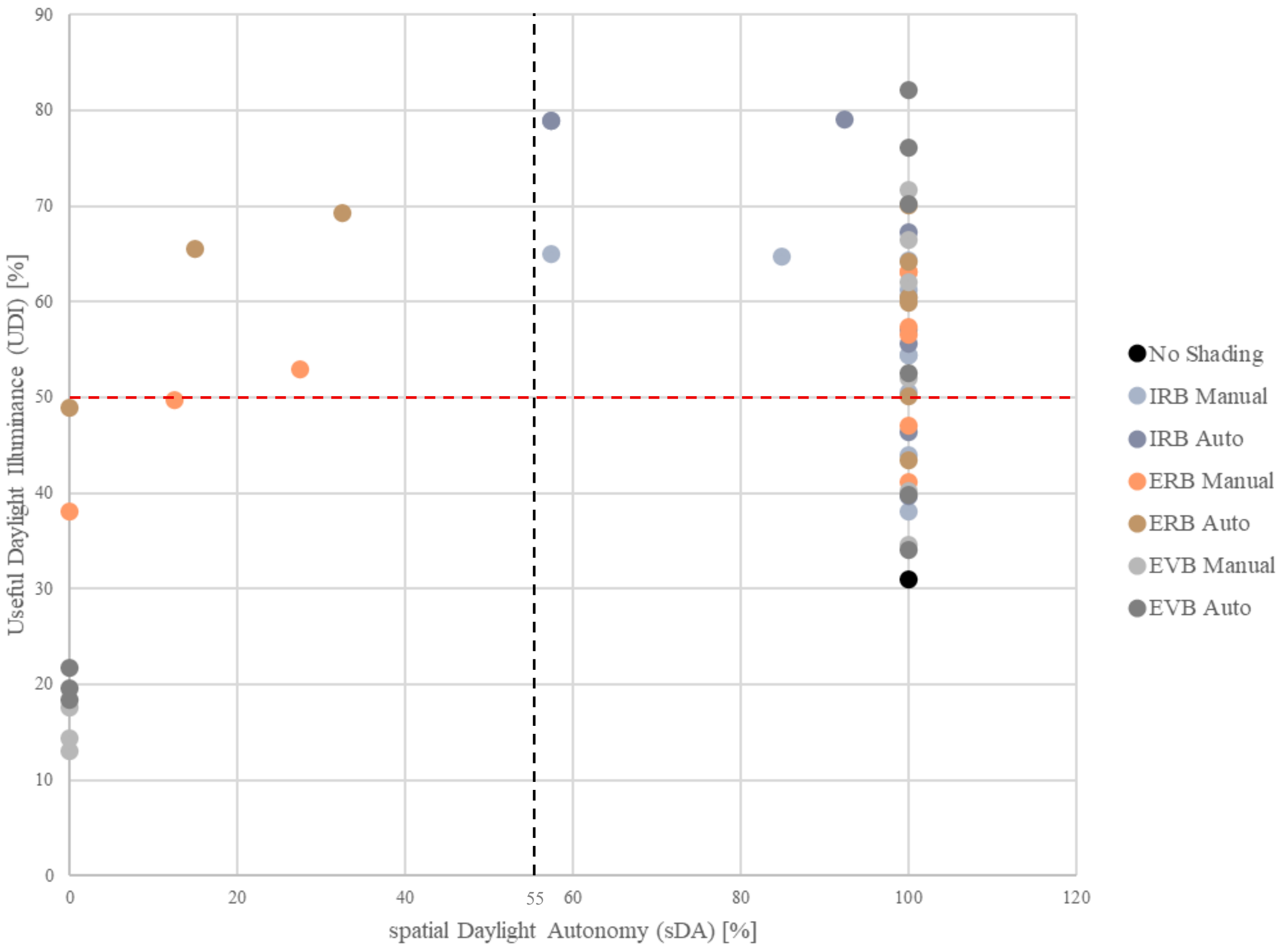

Figure 17: sDA and UDI for Different Shading Types and Control Strategies (all scenarios)

The sDA and UDI results show different patterns based on shading type.

- Interior Roller Blinds (IRB): IRB_30% consistently failed the UDI on clear and float glass due to insufficient shading against over-illumination. However, IRB_30% with coated float glass exceeded the threshold (54.0%-57.0%), making it the only successful 30% coverage configuration. This is because coated float glass (g value = 0.28) already significantly reduces solar heat gain, making even minimal shading sufficient to maintain illuminance within the useful range. IRB_50% and IRB_100% generally met the threshold. Then, automated control improved UDI by 14–18 percentage points for IRB_100% compared to manual control, as it responded more precisely to over-illumination.
- External Roller Blinds (ERB): ERB_100% with manual control showed contradictory results, with the sDA dropping to 0% (no daylight autonomy) while the UDI still passed at 52.9%. With manual control, the blinds sometimes opened during periods of low daylight, allowing useful daylight to enter. Under automated control, ERB_100% achieved more consistent results, with an sDA of 32.5% and a UDI of 69.2%. In contrast, ERB_30% often failed the UDI due to minimal coverage, which frequently caused over-illumination. ERB_50% consistently showed results above the threshold, making it the most reliable ERB configuration.
- External Venetian Blinds (EVB): EVBs show the clearest slat angle effect in this study. EVB_0° failed due to under-illumination (UDI 12.9% - 21.6%, sDA = 0%), while EVB_90° mostly failed due to over-illumination (UDI 34.0% - 40.1%). Only EVB_45° consistently had values above the threshold (62.0% - 82.1%). This suggests that for south-facing offices in Lund, a 45° slat angle provides a balance between blocking direct solar radiation and allowing sufficient daylight. Automated control shifted the UDI upward by 8–10 percentage points for EVB_45° across all glazing types.

4.2.3. Comparison Across Shading Types and Control Strategies

The best overall daylight performance was achieved by automated EVB_45° with coated float glass (UDI = 82.1%), which was the highest value among all 55 scenarios. Automated control consistently improved UDI compared to manual control for all shade types and configurations. The largest improvements occurred for EVB_45° (8–10 percentage points) and IRB_100° (14–18 percentage points). Table 12 summarizes which scenarios met the UDI ≥ 50% threshold. This determined which scenarios were included in the LCA comparison and in total there are 34 scenarios that exceed the threshold based on the functional unit.

Table 12: UDI threshold summary for all scenarios

No.	Configuration	Control	Glazing type	UDI [%]	FU met
0	Baseline (no-shading)	-	Clear	30.9	✗
1.	IRB_100%	Both	All glazing	64 – 79	✓
2.	IRB_50%	Both	Clear	50 – 56	✓
3.	IRB_30%	Both	Clear	38 – 40	✗
4.	IRB_50%	Both	Float	54 – 61	✓
5.	IRB_30%	Both	Float	43 – 47	✗
6.	IRB_50%	Both	Coated float	61 – 68	✓
7.	IRB_30%	Both	Coated float	54 – 57	✓
8.	ERB_100%	Manual	Clear	52.9	✓
9.	ERB_100%	Auto	Clear	69.2	✓
10.	ERB_100%	Manual	Float	49.7	✗
11.	ERB_100%	Auto	Float	65.4	✓
12.	ERB_100%	Both	Coated float	38 – 49	✗
13.	ERB_50%	Both	Clear	54 – 60	✓
14.	ERB_50%	Both	Float	57 – 64	✓
15.	ERB_50%	Both	Coated float	63 – 70	✓
16.	ERB_30%	Both	Clear	41 – 43	✗

17.	ERB_30%	Manual	Float	47.0	☓
18.	ERB_30%	Auto	Float	50.1	✓
19.	ERB_30%	Both	Coated float	57 – 60	✓
20.	EVB_0°	Both	All glazing	13 – 22	☓
21.	EVB_45°	Both	Clear	62 – 70	✓
22.	EVB_45°	Both	Float	66 – 76	✓
23.	EVB_45°	Both	Coated float	72 – 82	✓
24.	EVB_90°	Both	Clear	34 – 35	☓
25.	EVB_90°	Both	Float	40	☓
26.	EVB_90°	Both	Coated float	52	✓

4.3. Environmental Impact

The Life Cycle Assessment results in terms of Global Warming Potential (GWP), expressed in kgCO2eq per square metre of gross floor area per year [kgCO_2eq/m^{2}floor/year]. This normalisation follows the functional unit defined in 3.10.1. The results cover stages A1-A5, B2, B6, and C1-C4. Module D is excluded. Only scenarios meeting UDI ≥ 50% are included.

This section emphasizes that the total GWP for each scenario consists of two main components. First is the embodied carbon in façade elements such as glazing, blinds, and, for automated systems' components such as motors, the TaHoma switch, and sensors. Second, and more substantial part, is the operational energy B6, which represents the carbon emissions from the building's energy use over a 30-year period. Therefore, differences in total GWP between scenarios reflect differences in annual energy demand, particularly heating, cooling, and lighting, which differ across configurations, as explained in the section 4.1.2.

Figure 18 shows the total GWP for all scenarios within the goal functional unit. There are 34 scenarios consist of 16 pairs with the same configuration scenarios (manual and automated) and 2 scenarios that have no comparison, then with a no-shading scenario serving as the baseline, indicating better and worse GWP. The scenarios are grouped by shading type, control strategy, and glazing type. A dashed line at 14.14 kgCO_2eq/m^2 floor/year marks the no-shading baseline.

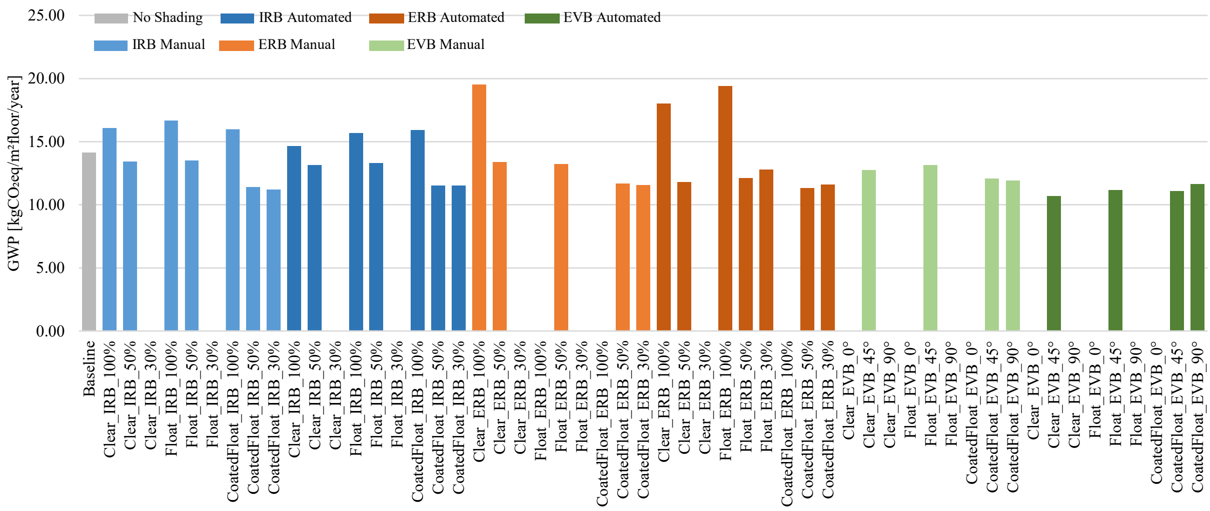

Figure 18: Total GWP [kgCO_2eq/m^{2}floor/year] for all valid scenarios. Scenarios with GWP = 0 are excluded (UDI < 50%).

The total GWP for these scenarios varies from 10.87 kgCO_2eq/m^2 floor/year (EVB_45° automated, clear glass) to 19.59 kgCO_2eq/m^2 floor/year (ERB_100% automated, float glass). Most scenarios fall within the expected range of 5–15 $kgCO_2/m^2$/year range for office buildings. However, two ERB_100% scenarios, both manual with clear glass (19.48 $kgCO_2eq/m^2$ floor/year) and automated with float glass (19.59 $kgCO_2eq/m^2$ floor/year), exceed this range. This is because the fully installed external blinds significantly reduce daylight, making lighting energy the main contributor to emissions.

Looking at Figure 18, one key observation is that automated systems generally produce lower GWP than manual systems in several cases. This is because automated systems open the blinds only when solar radiation is high enough to cause overheating and close them at other times to allow daylight in. This precise timing reduces cooling energy demand more effectively than manual operation. Lower cooling energy use reduces operational carbon, B6, which is the largest contributor to total GWP. GWP savings from automation depend on the shading type and glazing. For EVB_45°, automation reduces total GWP by between 0.79 $kgCO_2eq/m^2$floor/year and 1.88 $kgCO_2eq/m^2$floor/year compared to manual operation. For ERB_50°, savings range from 0.17 $kgCO_2eq/m^2$floor/year to 1.40 $kgCO_2eq/m^2$floor/year.

However, four cases show that manual control leads to a lower total GWP compared to automated control, as detailed in the Table 13. The GWP difference values in the table are calculated as automated GWPP minus manual GWP. Therefore, negative values (shown in red) indicate cases where automated control results in higher total GWP compared to manual control.

Table 13: The GWP total difference between manual and automated control for the LCA scenarios comparison

	Scenario	Manual GWP [$kgCO_2eq/m^2$floor/year]	Automated GWP [$kgCO_2eq/m^2$floor/year]	GWP Difference [$kgCO_2eq/m^2$floor/year]
1.	Clear_IRB_100%	16.24	14.98	1.26
2.	Clear_IRB_50%	13.59	13.43	0.16
3.	Float_IRB_100%	16.85	15.98	0.87
4.	Float_IRB_50%	13.67	13.63	0.04
5.	CoatedFloat_IRB_100%	16.15	16.24	-0.09
6.	CoatedFloat_IRB_50%	11.56	11.84	-0.28
7.	CoatedFloat_IRB_30%	11.37	11.81	-0.44
8.	Clear_ERB_100%	19.48	18.2	1.28
9.	Clear_ERB_50%	13.37	11.97	1.4
10.	Float_ERB_100%	-	19.59	-
11.	Float_ERB_50%	13.37	12.29	1.08
12.	Float_ERB_30%	-	12.99	-
13.	CoatedFloat_ERB_50%	11.68	11.51	0.17
14.	CoatedFloat_ERB_30%	11.54	11.79	-0.25
15.	Clear_EVB_45°	12.75	10.87	1.88
16.	Float_EVB_45°	13.15	11.36	1.79
17.	CoatedFloat_EVB_45°	12.05	11.26	0.79
18.	CoatedFloat_EVB_90°	11.89	11.83	0.06

In all scenarios, coated float glass already provides effective solar control due to its low g-value. As a result, automation offers only slightly extra cooling benefits. The carbon footprint of automation components such as motors, TaHoma switches, and sensors remains unchanged, regardless of the energy savings from their cooling. Therefore, the embodied and operational carbon emissions of this component slightly surpass the energy savings in these cases.

When comparing the shading types in Figure 18 and Table 13, the EVB scenario consistently achieves the lowest GWP of the three types, especially for automated control scenarios. The average GWP for EVB_45° auto is 11.17 $kgCO_2eq/m^2$floor/year, compared to 11.99 $kgCO_2eq/m^2$floor/year for ERB_50% auto and 13.57 $kgCO_2eq/m^2$floor/year for IRB_50% auto. This indicates that EVB's lower GWP results from reduced cooling demand, which directly decreases the main B6 component. The IRB scenario shows a higher GWP not because of increased embodied carbon (in fact, IRB has the lowest at 0.33 $kgCO_2eq/m^2floor/year$) but because the limited cooling reduction in the interior location results in relatively high B6 operational energy.

The impact of shading configuration on overall GWP follows the same pattern. For EVB, only the 45° configuration appears in the valid results, as EVB_0° and EVB_90° largely fail to meet the UDI threshold. EVB_45° consistently results in the lowest GWP within the EVB group. Regarding ERB, the 50% coverage configuration results in a lower total GWP than 100% coverage, despite 100% coverage providing a bigger cooling reduction. For IRB, both 50% and 30% coverage with coated float glass have the lowest GWP in the IRB group (11.37–11.84 $kgCO_2eq/m^2floor/year$), as the combination of moderate shading and low-g glass strikes a balance between cooling needs and lighting requirements.

4.3.1. Relationship between EUI and GWP

Figure 19 presents the relationship between total EUI and total GWP across all scenarios as a scatter plot, directly illustrating why operational energy is the primary driver of environmental impact throughout the lifecycle in this study.

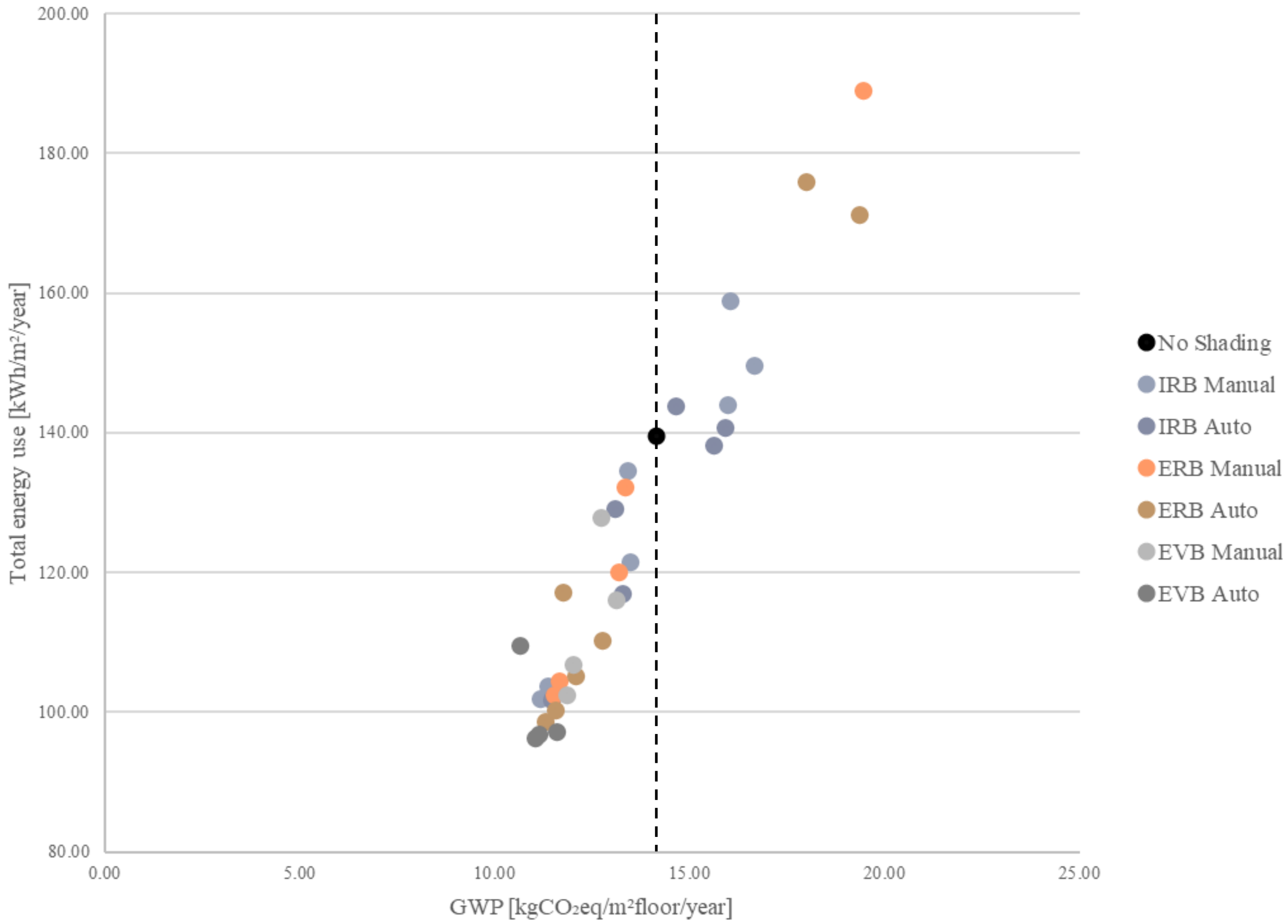

Figure 19: The relationship between EUI and GWP

The overall pattern shows a clear upward trend from the bottom left to the top right, where scenarios with lower EUIs generally have lower GWPs. The baseline point (EUI = 139.5 $kWh/m^2/year$, GWP = 14.14 $kgCO_2eq/m^2floor/year$) serves as a threshold to identify scenarios with lower and higher GWPs. Out of 34 valid scenarios, 25 are located to the lower left of the baseline, indicating they perform better than the baseline in both energy use and carbon emissions over their entire life cycle. The remaining nine points are located to the right of the baseline and all represent IRB_100% or ERB_100% configurations.

The dark green points (EVB Auto) form the densest cluster in the bottom left corner, with EUI values ranging from 96 to 111 kWh/m²/year and GWP from 10.87 to 11.83 $kgCO_2eq/m^2floor/year$, indicating that EVB_45° auto is the best performer on both metrics. The light green points (EVB Manual) are slightly to the right, but overall, the results show EVB forming the lowest cluster in the graph. The blue points (IRB) show a broader vertical spread from GWP 11.37 to 16.85 $kgCO_2eq/m^2floor/year$, with IRB_100% clear glass and float glass scenarios located in the upper right region of the baseline. The orange points (ERB) indicate the broadest range of data, with most ERB_50% scenarios grouping near EVB and IRB clusters in the lower left. However, three ERB_100% points are located in the far upper right corner with the highest EUI (171-188 kWh/m²/year) and GWP (18 – 19 $kgCO_2eq/m^2floor/year$) values in the entire study, illustrating the impact of excessive shading combined with poor glazing quality.

Within each shading group, the automated points generally fall slightly lower and to the left of the manual points, indicating operational energy savings from automated controls. The only exception is the IRB with coated float glass, where automated points are slightly higher in GWP despite similar EUI, as described in the previous section.

4.3.2. Contribution by Component

Figure 20 presents the average GWP contribution by component for each shading, averaged across all valid scenarios within that group.

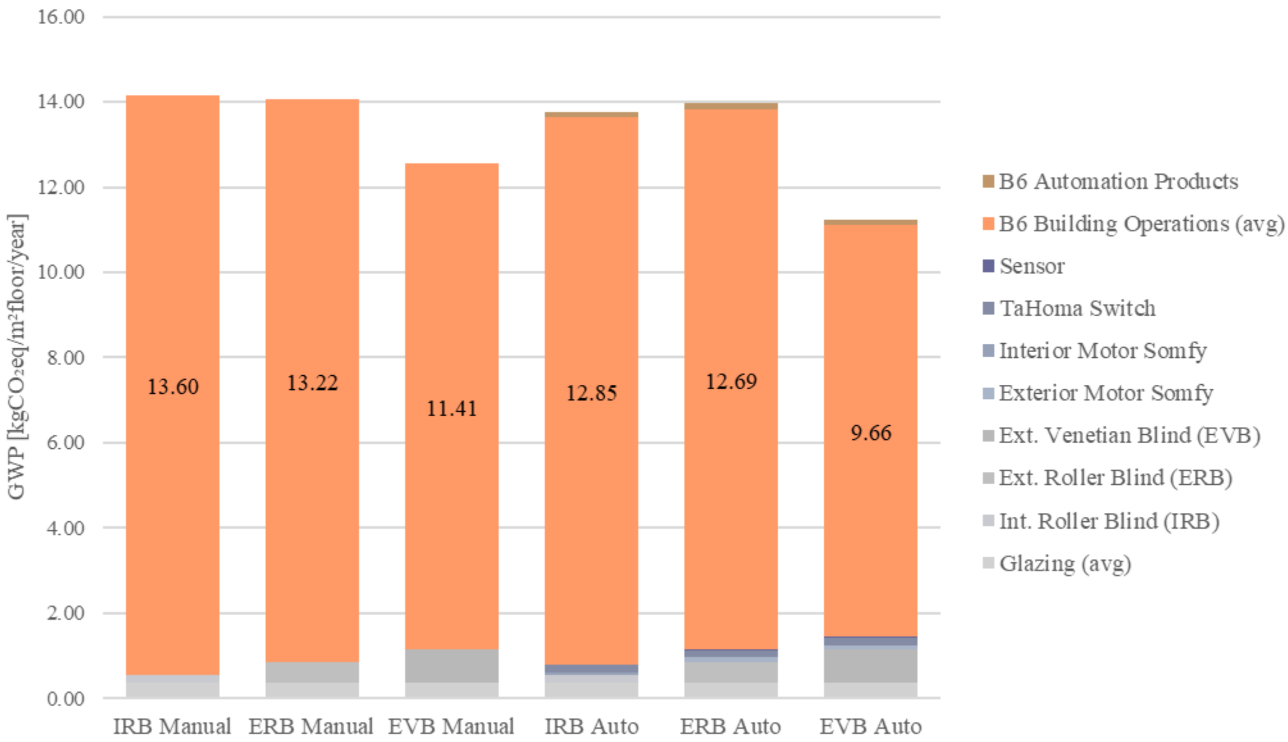

Figure 20: Average GWP [$kgCO_2eq/m^2floor/year$] by component for each shading type and control group. Each bar represents the average of all valid scenarios in that group.

The most noticeable point is that B6's operational energy accounts for the largest share in each group. B6 ranges from 9.66 $kgCO_2eq/m^2floor/year$ (Automated EVB) to 13.60 $kgCO_2eq/m^2floor/year$ (Manual IRB), within a group average of 11.30 to 14.19 $kgCO_2eq/m^2$floor/year. This means that building operational energy contributes 85–96% of the total GWP, while other components such as blinds, motors, and automation hardware contribute only about 4–15%.

In the B6 graph across six groups, the automated EVB has the lowest B6 value at 9.66 $kgCO_2eq/m^2$floor/year, which is significantly lower than the other groups. This is because the automated EVB_45° achieves the largest cooling demand reduction in this study. Generally, B6 values decrease from manual to automated across shading types: IRB drops from 13.60 to 12.85, ERB from 13.22 to 12.69, and EVB from 11.41 to 9.66. The B6 reduction through automation is most notable for EVB (1.75 $kgCO_2eq/m^2$floor/year) and least for IRB (0.75 $kgCO_2eq/m^2$floor/year), indicating differences in how effectively each shading type reduces cooling demand through appropriate automation.

Table 14: The detailed values of GWP [$kgCO_2eq/m^2$floor/year] by component for each shading type and control group

Components	IRB Manual	ERB Manual	EVB Manual	IRB Auto	ERB Auto	EVB Auto
Glazing (avg)	0.38	0.38	0.38	0.38	0.38	0.38
Int. Roller Blind	0.17			0.17		
Ext. Roller Blind		0.48			0.48	
Ext. Venetian Blind			0.77			0.77
Exterior Motor Somfy					0.10	0.10
Interior Motor Somfy				0.06		
TaHoma Switch				0.18	0.18	0.18
Sensor				0.01	0.01	0.01
B6 Automation Products				0.14	0.13	0.13

Glazing contributed 0.38 $kgCO_2eq/m^2$/year evenly across the six groups because the same three types of glazing were averaged across each group. The hidden carbon of the blinds varied depending on the glazing type: EVB had the highest at 0.77 $kgCO_2eq/m^2$/year due to its aluminum material, followed by ERB at 0.48 and IRB at 0.17 $kgCO_2eq/m^2$/year. EVB had the highest hidden carbon among the three glazing types but had the lowest overall GWP, suggesting that the hidden carbon of the glazing device itself is less significant than its effectiveness in reducing operational energy.

For automation components, TaHoma switches add 0.18 $kgCO_2eq/m^2$/year to all automation groups. Exterior Somfy motors add 0.10 $kgCO_2eq/m^2$/year for ERB Auto and EVB Auto, while interior motors add 0.06 $kgCO_2eq/m^2$/year for IRB Auto. SUNTEIS sensors contribute 0.01 $kgCO_2eq/m^2$/year. In total, all automation hardware adds 0.39 $kgCO_2eq/m^2$/year for IRB automation and 0.42 $kgCO_2eq/m^2$/year for ERB and EVB automation. Even with these additions, Auto EVB and Auto ERB still achieved lower total averages than their manual counterparts (EVB: 11.30 $kgCO_2eq/m^2$/year for automated compared to 12.43 $kgCO_2eq/m^2$/year for manual; ERB: 14.03 $kgCO_2eq/m^2$/year for automated compared to 13.95 $kgCO_2eq/m^2$/year for manual). For IRB, the total averages were 13.97 $kgCO_2eq/m^2$/year for automated and 14.19 $kgCO_2eq/m^2$/year for manual. This indicates that the B6 savings from automation outweigh the additional embodied carbon in the hardware in most cases, except for Auto ERB, which produced a slightly higher total average than Manual ERB.

4.3.3. Life Cycle Stage Distribution

Figure 21 presents the GWP contribution for each product component at various life cycle stages. While Figure 20 shows the average contribution across all scenario groups, Figure 21 breaks down each component into manufacturing (A1–A5), use (B2/B4), and end-of-life (C2–C4) stages.

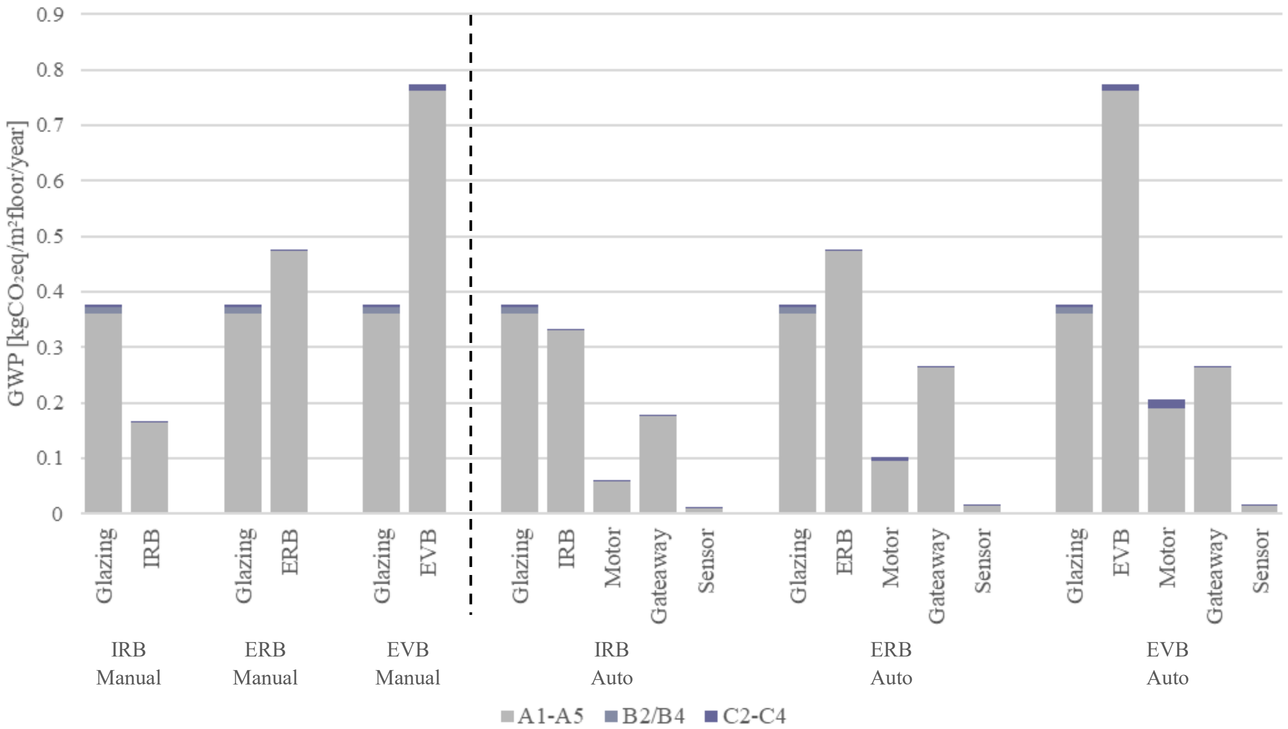

Figure 21: Life cycle stage contribution to GWP by each component

Across all components, manufacturing stages A1–A5 are the dominant contributors. For glazing and all three types of blinds (IRB, ERB, EVB), almost all impacts are concentrated in A1–A5, with no B2 maintenance data reported for blinds in the EPD, and only negligible end-of-life contributions from C2–C4.

For automation components, motors, gateways, and sensors, the same pattern is observed, showing A1–A5 as the dominant stages, with only a very small end-of-life contribution from C2–C4 visible in the figure. This indicates that the environmental impact of automation hardware is almost entirely determined by the manufacturing stage, making material and production choices the primary factors in reducing its carbon footprint.

Overall, the breakdown of lifecycle stages confirms that the embodied carbon in the manufacturing stage drives the environmental impact of all façade components throughout the system, regardless of whether they are passive (glazing, blinds) or active (motors, gateways, sensors).

4.4. The Summary of The Best and Worst Scenarios

Table 15 presents a summary of all the best and worst-performing of the comparison scenarios based on the five performance metrics used in this study.

Table 15: The summary of the best and worst within comparison scenarios in LCA

Metric	Best scenario	Value	Worst scenario	Value	Unit
UDI	Coated float_Auto_EVB_45°	82.1	Float_Auto_ERB_30%	50.1	%
sDA	EVB/ERB_50% scenarios	100	Float_Auto_ERB_100%	15	%
Overheating hours	Coated float_Auto_EVB_45°	1.2	Float_Manual_IRB_50%	37.27	%

EUI	Coated float_Auto_EVB_45°	96.1	Clear_Manual_ERB_100%	188.8	kWh/m^2/year
Peak cooling	Coated float_Auto_EVB_45°	42.0	Clear_Manual_IRB_50%	237.5	W/m^2
Total GWP	Clear_Auto_EVB_45°	10.87	Float_Auto_ERB_100%	19.59	kgCO_2eq/m^{2}floor/year

Based on the table above, coated float_auto_EVB_45° is the top performer in five out of six metrics: UDI, overheating hours, EUI, and peak cooling. The only metric where it was not on top of the list was the total GWP LCA, where it ranked second at 11.26 kgCO_2eq/m^{2}floor/year, just behind the automated EVB_45° with clear glass at 10.87 kgCO_2eq/m^{2}floor/year. On the other hand, ERB_100% auto with float glass was the worst-performing scenario across two metrics: sDA of 15% and total GWP of 19.59 kgCO_2eq/m^{2}floor/year. This configuration illustrates how shading devices that block excessive daylight can reduce cooling needs but increase lighting energy consumption. This increased lighting energy use outweighs the savings in cooling, resulting in total energy consumption exceeding the no-shading baseline.

Three overall conclusions can be drawn from this comparison:

1. External shading is critical to the thermal performance of south-facing facades with high WWR. Interior roller blinds have a limited cooling effect because solar radiation has already passed through the glazing and heated the room before the blinds can operate. External shading intercepts the radiation before it reaches the glazing, which is why EVBs and ERBs consistently outperform IRBs in both cooling requirements and overheating across all glazing types and control strategies.
2. EVB_45° is the best overall shading configuration. It is the only configuration that consistently performs well in terms of energy, thermal comfort, daylight, and the impact throughout the entire lifecycle. The 45° slat angle rejects high-angle summer sunlight while allowing low-angle winter sunlight and diffused daylight in, avoiding the excessive shading issues that make EVB_0° and EVB_90° perform worse than the middle position. Coated float glass consistently reinforces these benefits across all metrics.
3. Automated external shading achieves a lower total lifecycle GWP than manual shading in most cases, even after accounting for additional hardware such as motors, TaHoma switches, and sensors. This is because B6 operational energy dominates the total GWP (85–96% of the total), so the energy savings from automated controls over 30 years exceed the one-time carbon footprint of the automation components. This directly addresses the core research question of this thesis: is automated facade shading environmentally justified over the 30-year study period when external shading is used.

5. Discussion

The findings presented in this study are case-specific and should be understood within the assumptions and boundary conditions applied in the simulations. The results are influenced by several factors, including the office size, façade area, glazing ratio, and envelope properties as well as system-related factors such as the HVAC configuration, and heating-cooling supply conditions. The observed differences between scenarios are therefore specific to the tested case and modelling assumptions, and cannot be directly generalised to other building types, climates, or system configurations. The main contribution of this thesis is to provide a methodology and framework for evaluating automated façade shading systems across multiple performance areas, such as energy use, daylight quality, thermal comfort, and life-cycle environmental impact, and to demonstrate how these areas interact in a real office setting.

5.1. Effects of the 70% Window-to-Wall Ratio

One of the most important contextual factors shaping all the results in this study is the window-to-wall ratio (WWR) of 70%. This is significantly higher than what is typically found in office buildings, where WWRs typically range between 30% and 40% (Bülow-Hübe, 2008).

In a building with a 30% WWR, the glazing area would be approximately half as large. This leads to two main effects. First, solar heat gain would be significantly lower, meaning cooling requirements would be reduced and the overheating problem that dominates this study would be less severe. Second, the difference in performance among shading configurations would be less different; with smaller windows, even partially open blinds with 50% coverages provide sufficient solar control, and the dramatic gap between IRBs, which is barely effective at reducing cooling, and EVBs_45°, which are highly effective, would become much smaller.

On the daylight side, with smaller windows, fewer scenarios would fail to meet the UDI threshold because the risk of over-illumination is reduced. Scenarios like EVB_90°, which many failed in this study, may qualify with a 30% WWR simply because less solar radiation enters, even without shading. This will affect which scenarios qualify for LCA comparison.

What remains unchanged with WWR is the fundamental physical relationship between shading type and thermal behavior. External shading always intercepts solar radiation before it enters the room, while interior shading cannot, regardless of window size. Similarly, the finding that automated controls reduce energy demand more effectively than manual controls is independent of WWR, as it reflects the timing of implementation. Therefore, the qualitative rankings from this study likely remain valid at lower WWRs, although the amount of the difference will be smaller.

5.2. Energy Performance: All Shading Types Show Similar Heating and Cooling Totals with Coated Float Glass

Looking at the coated float glass group in

Figure 11, it shows that across all three shading types and all configurations: IRB, ERB, and EVB have very similar heating and cooling totals, ranging between 30.5 and 33.6 kWh/m²/year. With clear glass, the same configurations show much higher and more dispersed totals, ranging from 57 to 65 kWh/m²/year.

Coated float glass has a very low solar heat gain coefficient (g-value = 0.28), meaning it blocks most solar radiation before shading does anything. So, regardless of the type of shading added, whether internal or external, fully closed or partially open, the shading only addresses a small portion of the solar heat gain not already addressed by the coated float glass. Because the remaining solar heat gain is minimal and similar across all configurations, the combined heating and cooling totals are similar.

In summary, with coated float glass, the glass layers do most of the work, and the shading devices have a smaller impact to make a significant difference in the total energy. With clear glass, the glass layers do less, so shading devices have a larger effect and create more noticeable differences between configurations.

5.3. EUI and Overheating Hours

This section explains the relationship between total energy use intensity (EUI) and thermal comfort across all shading scenarios. First, it examines the trade-off between reducing overheating and overall energy use, then analyzes how shading type and control strategy affect these two performance indicators.

5.3.1. Reducing Overheating Does Not Always Reduce Energy

Overall, a clear trade-off exists between thermal comfort and overall energy consumption. The EVB_0° auto scenario has the lowest overheating hours, with only 0.2% of occupancy hours above 26°C. However, this same scenario has the highest EUI in the study, exceeding 200 kWh/m²/year, because it blocks so much daylight that the lighting system operates almost continuously. In other words, achieving near-perfect thermal comfort through aggressive shading comes at a significant energy cost.

This reflects a design trade-off: reducing cooling loads by blocking more solar radiation enhances thermal comfort but also decreases daylight, leading to higher lighting energy use. These opposing effects make the relationship between EUI and overheating hours non-linear. Some configurations, like EVB_45° auto, result in low overheating hours with a low EUI, whereas others, such as EVB_0° auto, maintain low overheating hours at a higher EUI or experience high overheating hours at a low EUI, especially in partially open IRB configurations.

5.3.2. The Effect of Shading Type and Control Strategy

External shading types (EVB and ERB) consistently outperform interior shading (IRB) regarding thermal comfort. This indicates that shading positioned outside, such as external blinds intercepting solar radiation before it enters the room, effectively prevents heat from building up inside. In contrast, IRB can only intercept radiation after it passes through the glazing, where some heat has already been absorbed. Even with full coverage, the automated IRB_100% with clear glass results in 21.4% overheating hours, which is more than double the Passive House benchmark of 10%.

Automated control consistently reduced overheating hours compared to manual control for the same configuration. The automated system activates the blinds when solar radiation exceeds 120 W/m², which is a more reliable thermal trigger than the occupant-driven, illumination-based decisions in the manual mode. Manual control relies on occupant actions, and as modeled with Lightswitch-2002, occupants often leave the blinds in the same position for hours even when conditions change. This results in overheating under manual control, as the blinds are sometimes left open when solar radiation is already high.

5.4. Daylight Performance: Good-Performing Configurations for Daylight

The highest daylight quality was achieved with the automated 45° EVB using coated float glass, achieving sDA = 100% and UDI = 82.1%. This result exceeded the no-shading baseline UDI of 30.9%. The baseline's poor performance was not due to insufficient light but because of excessive and long hours of illumination. In Lund, south-facing windows with a 70% WWR produce illuminance above 3 000 lux during most working hours, which the UDI considers excessive rather than beneficial daylight. The automated 45° EVB addressed this problem by opening the blinds during high-sun periods, directing light onto the ceiling and walls through angled slats rather than directly onto the work surface. As a result, illuminance remains more consistently within the useful range.

The second finding shows why the manual IRB configuration performed relatively well on the daylight metric, surpassing some external shading options. The IRB fabric is translucent, not opaque. When the blinds are open, they diffuse daylight instead of blocking it entirely, ensuring a more even light distribution across the workspace. This helps prevent over-illumination peaks that drop UDI below the threshold, as seen in the baseline scenario, while still allowing enough light for proper illuminance. Additionally, the manual control configuration generally keeps the blinds closed for most of the day once it is activated in the morning. This leads the room to spend more time in moderate illumination, because neither very bright nor very dark conditions occur.

5.5. The Environmental Impact (LCA)

One of the questions motivating this study was whether adding automation hardware to shading systems, such as motors, gateways, and sensors, provides environmental benefits over their entire life cycle. The results indicate that this is true in most cases, but not in all, and the reasons for this need to be clarified.

5.5.1. Operational Energy as the Primary Driver of GWP

It was initially thought that shading devices and the addition of automation products would play a significant role in influencing total GWP. However, the results revealed that building operational energy (B6) accounted for 85% to 95% of total GWP across all scenarios. Shading, glazing, motors, and automation component together accounted for only 5% to 15% of the remaining energy.

This means that the most important factor determining the environmental impact throughout the lifecycle of a facade scenario is the building's annual energy use, primarily for cooling, as well as heating and lighting. Any shading configuration that reduces annual energy demand will have a significant positive effect on total GWP, while the embodied carbon of the shading material itself is a relatively small contributor.

Operational energy dominates mainly because of the 30-year study period. While embodied carbon is a one-time cost during manufacturing and at end-of-life, operational energy accumulates annually over 30 years. Even small differences in annual energy demand can significantly impact total GWP over 30 years. For example, the cooling demand difference between automated EVB_45° (13.2 kWh/m²/year) and manual EVB_45° (31.1 kWh/m²/year) with clear glass is 17.9 kWh/m²/year. Over 30 years, using the Swedish grid emission factor (0.115 $kgCO_2/kWh$), this represents a total cooling saving of $17.9 \times 30 \times 0.115 = 61.8$ $kgCO_2eq/m^2$. This exceeds five times the embodied carbon of the TaHoma switch alone over 30 years ($0.35 \times 30 = 10.5$ $kgCO_2eq/m^2$).

5.5.2. Comparison Between Operational Saving and Embodied Carbon

The comparison between operational savings and embodied carbon evaluates the relationship between the annual operational carbon savings achieved through automation and the annual embodied carbon associated with the automation components. Since both values are measured using the same functional unit ($kgCO_2eq/m^2$floor/year), the comparison indicates how large the operational savings are relative to the embodied carbon contribution of the automation component.

For example, for an automated EVB_45° with clear glass compared to the same configuration under manual control, the calculation is as follows:
The annual GWP savings from reduced energy demand are calculated as follows: cooling savings (17.9 kWh/m²/year) and lighting savings (4.0 kWh/m²/year) are multiplied by the electricity emission factor (0.115 $kgCO_2/kWh$). The heating penalty (3.9 kWh/m²/year) is multiplied by the district heating emission factor (0.011 $kgCO_2/kWh$) and subtracted from the electricity-related savings. The total annual operational saving is therefore: $(17.9 + 4.0) \times 0.115 - 3.9 \times 0.011 = 2.48$ $kgCO_2eq/m^2$floor/year.
The total embodied carbon of the automation component per year consists of: motors (0.25) + TaHoma switch (0.35) + sensor (0.02) = 0.62 $kgCO_2eq/m^2$floor/year. Comparing the component embodied carbon with the operational savings gives $0.62 \div 2.48 = 0.25$. This means that the annual embodied carbon of the automation components represent approximately 25% of the annual operational carbon savings.

This relationship explains why the automated EVB_45° results in a lower total GWP than the manual EVB_45° despite the additional component. For most external shading configuration in this study, the annual operational carbon savings are significantly larger than the annual embodied carbon contribution of the automation component, giving the overall environmental benefit.

The situation is different for two exceptional cases: IRB_50% and IRB_100% with coated float glass. In these cases, the coated float glass already effectively limits solar heat gain, so the automated system achieves only small additional cooling savings compared to the manual system. For IRB_100% with coated float glass, the cooling saving is only 0.5 kWh/m²/year (manual = 21.25, auto = 20.74 kWh/m²/year). Lighting demand is almost identical between manual and automated control, and heating demand is slightly lower under automated control (manual = 11.8, auto = 10.9 kWh/m²/year). The full annual GWP saving is therefore $(0.5 + 0) \times 0.115 - (-0.9) \times 0.011 = 0.067$ $kgCO_2eq/m^2$floor/year. The automation hardware for IRB adds 0.54 $kgCO_2eq/m^2$floor/year in embodied carbon, which is eight times the annual operational energy savings of 0.067 $kgCO_2eq/m^2$floor/year. As a result, the automated IRB configurations with coated float glass produce higher total GWP values than the corresponding manual scenarios. Since the coated float glass already provides strong solar control performance, the additional contribution from automated blind operation becomes relatively small, while the embodied carbon associated with the automation hardware remains significant.

5.5.3. Influence of Grid Carbon Intensity

All GWP values in this study were calculated using the Öresund grid emission factor of 0.115 $kgCO_2/kWh$. Sweden's electricity grid is relatively clean due to its high share of hydropower and wind energy. However, many countries in Europe and the world have much higher grid emission factors, which would significantly change the LCA results.

To illustrate this, the GWP of B6 was recalculated for a building in Poland, where the current grid emits approximately 0.75 $kgCO_2/kWh$, approximately 6.5 times higher than Sweden's. It is important to note that only electricity-based energy uses changed: cooling, lighting, and electric equipment. Heating from district heating remained the same. For the no-shading baseline, the electricity-based B6 in Sweden is $(49.7 + 23.7 + 47.7) \times 0.115 = 13.93$ $kgCO_2eq/m^2floor/year$. In Poland, the same electricity usage produces $(49.7 + 23.7 + 47.7) \times 0.75 = 90.83$ $kgCO_2eq/m^2floor/year$, and adding the district heating contribution $(18.3 \times 0.011 = 0.20)$ gives a total B6 of approximately 91 $kgCO_2eq/m^2floor/year$, more than six times the Swedish value of 14.14 $kgCO_2eq/m^2floor/year$.

The consequence for automation is that energy savings become much more valuable in terms of GWP. For the comparison of automated versus manual EVB_45° with clear glass, the annual GWP savings in Sweden are calculated as: $(17.9 + 4.0) \times 0.115 - 3.9 \times 0.011 = 2.48$ $kgCO_2eq/m^2floor/year$, where 17.9 $kWh/m^2/year$ is cooling savings, 4.0 $kWh/m^2/year$ is lighting savings, and 3.9 $kWh/m^2/year$ is the heating penalties. The annual embodied carbon of the automation component is 0.62 $kgCO_2eq/m^2floor/year$. Comparing the embodied carbon with the annual operation saving gives $0.62 \div 2.48 = 0.25$. This means that the annual embodied carbon of the automation component represent around 25% of the annual operational savings in Sweden.

In Poland, only the electricity emission factor changes, while the district heating emission factor remains the same. The annual GWP savings become $(17.9 + 4.0) \times 0.75 - 3.9 \times 0.011 = 16.38$ $kgCO_2eq/m^2floor/year$. Comparing the embodied carbon with the operational savings shrinks to $0.62 \div 16.38 = 0.0038$, meaning that annual embodied carbon only approximately 3.8% of the operational carbon savings in Poland. Even in the two exceptional IRB cases with coated glass, automation control would likely provide a net GWP benefit in Poland, as the operational carbon savings from reduced cooling become much more substantial due to the higher electricity emission factor.

The reason Poland benefits more from automation is that the dirtier the electricity grid, the more carbon is saved each time energy use is reduced. In Sweden, saving 1 kWh of electricity eliminates 0.115 kg CO_2. In Poland, the same saving of 1 kWh eliminates 0.75 kg CO_2. The automated shading system saves the same amount of cooling energy (17.9 $kWh/m^2/year$) regardless of installation location, but in Poland, these savings produce 6.5 times greater carbon benefits. On the other hand, the carbon embodied in the automation hardware is fixed, produced in the same way, and adds 0.62 $kgCO_2eq/m^2/year$ to the total embodied carbon, regardless of location.

5.5.4. Effect of a Longer Study Period

This study used a 30-year reference study period, which is a common choice in building LCAs and aligns with EN 15978 recommendations for office buildings. However, it is important to consider how the results will be reflected over a longer lifespan, such as 50 years.

For products with a 30-year lifespan, such as glass, EVB blinds, and ERBs, extending the study period to 50 years would require additional replacements, adding another embodied carbon cycle. For automation components with a 10-year lifespan, such as TaHoma switches and sensors, they would require five replacements, further increasing their embodied carbon contribution. However, operational energy savings would also accumulate over another 20 years, which at current rates would add additional GWP savings.

Specifically for glazing, the 30-year study period means that end-of-life glazing is not included for any product in this study, as its lifespan exactly aligns with the study period. Over a period beyond 50 years, the glazing would need to be replaced, which would generate carbon emissions due to end-of-life and remanufacturing processes that currently do not exist. This is a particularly relevant consideration for coated float glass, which requires more frequent replacement than standard clear glass in some applications. Future studies with longer lifespan should explicitly model the glazing replacement cycle and its impact on total GWP.

5.6. LCA sensitivity

The sensitivity analysis was conducted to evaluate how changes in the environmental impact assumptions of the automation component affect the LCA results. The three scenarios defined in the methodology are compared with the baseline results to assess whether variations in motor data and automation assumptions affect the total GWP values and overall ranking of the cases. Overall, the results show that the ranking is relatively robust, as the highest-performing scenarios remain largely consistent across all three sensitivity scenarios. Only minor shifts in ranking occur between scenarios with very similar GWP values, indicating that the overall conclusions are not significantly affected by the uncertainty in the automation component data.

In Scenario S1, where the GWP values of all automation components are reduced by 20%, the overall ranking pattern remains very similar to the baseline case. Automated EVB configuration continues to dominate top rankings due to its low EUI and relatively low GWP. The three best-performing scenarios remain with automated control. The first rank is Clear_EVB_45°, achieving GWP values around 10.87 $kgCO_2eq/m^2floor/year$ and an EUI of 109.43 $kWh/m^2/year$, followed by Coated Float_ EVB_45° and Float_EVB_45° with GWP values of 11.26 and 11.36 $kgCO_2eq/m^2floor/year$, respectively, and EUI values around 96 kWh/m^2. Reducing the environmental impact of the automation components slightly improved the performance of automated shading systems. However, only minor shifts in the ranking were noted, and the overall performance trend stayed consistent with the baseline. Most notable differences appear between scenarios with very similar GWP values, typically differing by less than 0.1-0.2 $kgCO_2eq/m^2floor/year$. For example, Clear_ERB_50% coverage with automated control slightly decreases from 11.96 to 11.87 $kgCO_2eq/m^2floor/year$, shifting its position relative to the manual control coated float_EVB_90°, which is 11.89 $kgCO_2eq/m^2floor/year$ in this LCA scenario.

In Scenario S2, increasing the embodied impacts of automation components by 20% results in a relatively stable ranking. However, automated scenarios show slightly higher increases in total GWP compared to manual cases because this increase is applied specifically to production stages where automation impacts are most significant. For example, in the baseline case and scenario S1, the third top performing is automated Float_EVB_45; in scenario S2, it shifts to fourth place due to its rising number into 11.46 $kgCO_2eq/m^2floor/year$, exchanging positions with manual Coated float_IRB_30%, which has 11.37 $kgCO_2eq/m^2floor/year$. Despite this, automated EVB scenarios continue to perform well. For example, Coated Float_EVB_90° with automated control maintains a low EUI of 97.04 $kWh/m^2/year$ and a GWP of 11.92 $kgCO_2eq/m^2floor/year$. Some automated ERB and IRB scenarios move slightly downward in the ranking compared to the baseline, mostly when their operational energy savings are smaller. Even so, the ranking differences remain minimal, with only slight changes mostly among mid-ranked cases with similar performance. The gap between the best and worst scenarios still mainly depends on operational energy demand rather than changes in automation embodied impacts.

Scenario S3, which uses an alternative PEP dataset for the motor components, shows only slight changes in ranking compared to the baseline. The top scenarios remain largely unchanged. Automated EVB configurations continue to perform well, especially for coated float glazing and moderate slat angles such as 45°. Some automated control switch positions upward under manual control because of lower GWP values compared with the baseline ranking. For example, Coated float_IRB_100% with automated control has GWP values of 16.24 and decreasing to 16.22 $kgCO_2eq/m^2floor/year$, exchanging positions with manual Clear_IRB_100% at 16.23 $kgCO_2eq/m^2floor/year$. Similarly, automated float_ERB_100% has a value of 19.59 and is reduced to 19.48 $kgCO_2eq/m^2floor/year$, shifting upward relative to manual Clear_ERB_100% at 19.48 $kgCO_2eq/m^2floor/year$.

There are some clear trends across all sensitivity scenarios. First, automated EVB generally remains among the top performers in balancing operational energy efficiency and embodied environmental impacts. Its ability to lower cooling demand and EUI compensates for the increased embodied impacts from automation components. Second, scenarios with coated float glazing frequently achieve lower total GWP and EUI than clear glazing cases, showing the importance of glazing performance in reducing operational energy. Third, some IRB and ERB scenarios show slight changes in ranking shifts across different sensitivity scenarios, especially among cases with similar GWP values. Slight variations in automation component impacts can be enough to change the ranking order.

Overall, the sensitivity analysis indicates that the ranking pattern remains relatively stable across the three scenarios, despite some variations in automation data. Minor shifts mainly happen between cases with similar GWP values. The best-performing scenarios, especially automated EVB configurations, remain mostly consistent. This means that the study’s conclusions are reliable, and the preferred shading strategies remain similar under different assumptions about the environmental impacts of the automation components.

6. Conclusion

This study evaluated a no-shading baseline and 54 facade configurations combining three shading types (IRB, ERB, EVB), three glazing types, and two control strategies (manual and automated) in a south-facing test office room in Lund, Sweden. Performance was assessed across four dimensions: daylight quality (UDI and sDA), thermal comfort (overheating hours), energy demand, and lifecycle environmental impact (GWP, ISO 14040/14044). From the 54 scenarios, 34 met the functional unit threshold of UDI ≥ 50% and were included in the LCA comparison with the baseline.

Four key conclusions can be drawn:

- External automated shading consistently outperformed interior shading across all metrics. The best overall scenario was the automated EVB_45° with coated float glazing, which achieved a UDI of 82.1%, only 1.2% overheating hours, an EUI of 96.1 kWh/m²/year, and a peak cooling load of 42.0 W/m². In contrast, the best scenario for IRB with the same glazing still showed 7.9% overheating hours and a peak cooling of 115.9 W/m². The position of external versus internal shading devices was more important than any other design parameter in this study.
- A 45° slat angle is a critical design choice for Venetian blinds. EVB_0° and EVB_90° both performed worse than EVB_45°. This is because EVB_0° blocks too much solar radiation, increasing heating and lighting energy, while EVB_90° lets in too much solar radiation, causing overheating and glare. Only EVB_45° strikes the right balance for the Swedish climate, blocking high-angle summer sunlight while allowing low-angle winter sunlight and diffuse daylight in.
- Automated control is environmentally justified in most scenarios despite the additional embodied carbon associated with motors, TaHoma switches, and sensors. Across the LCA comparison scenarios, the automated scenario continues to achieve a lower total lifecycle GWP than the manual control scenarios due to larger operational carbon savings from reduced cooling and lighting demand. For the automated EVB_45° with clear glass, the annual operational carbon saving compared to manual control was 2.48 $kgCO_2eq/m^2floor/year$, while the annual embodied carbon of the automation component was 0.62 $kgCO_2eq/m^2floor/year$. This means that embodied carbon represents only around 25% of the operational carbon savings. In a high-carbon grid like Poland (0.75 $kgCO_2/kWh$), the same comparison decreased to about 3.8%, showing that automation has a greater environmental benefits in regions with higher electricity carbon emissions.
- Coated float glass enhances the benefits of external shading but reduces the benefits of automation for interior shading. With coated float glass, all shading configurations, regardless of type or coverage, produce very similar combined heating and cooling totals (30–34 kWh/m²/year), as the glazing already performs most of the thermal work. However, this total is not the same with clear glass, where the range is 57–65 kWh/m²/year. Therefore, it can be argued that the right glazing is as important as the right shading type, and the two should always be evaluated together rather than separately.

The findings of this study are specific to the configuration tested: a single south-facing office room with a 70% of window-to-wall ratio (WWR) under Swedish climate conditions. The qualitative rankings, with EVB_45° being the best, IRB being the worst, and automated being better than manual for external shading, are expected to hold in similar contexts, but the differences between configurations are likely to be smaller at lower WWR. In regions with higher grid carbon intensity, the environmental benefit for automated external shading is even stronger than shown here.

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Annex A. Simulation Parameters

Table 16: The list schedule for energy and daylight simulation (Igrexas, 2024)

Hour	Occupancy schedule		Lighting schedule		Equipment schedule		Heating setpoint		Cooling setpoint	
	Mon-Sat	Sun	Mon-Sat	Sun	Mon-Sat	Sun	Mon-Sat	Sun	Mon-Sat	Sun
1	0.0	0.0	0.2	0.2	0.4	0.2	15.6	15.6	29.4	29.4
2	0.0	0.0	0.2	0.2	0.4	0.2	15.6	15.6	29.4	29.4
3	0.0	0.0	0.2	0.2	0.4	0.2	15.6	15.6	29.4	29.4
4	0.0	0.0	0.2	0.2	0.4	0.2	15.6	15.6	29.4	29.4
5	0.0	0.0	0.2	0.2	0.4	0.2	15.6	15.6	29.4	29.4
6	0.0	0.0	0.2	0.2	0.4	0.2	15.6	15.6	29.4	29.4
7	0.1	0.0	0.2	0.2	0.5	0.2	21.1	15.6	23.9	29.4
8	0.2	0.0	0.3	0.2	0.5	0.2	21.1	15.6	23.9	29.4
9	1.0	0.0	0.7	0.2	1.0	0.2	21.1	15.6	23.9	29.4
10	1.0	0.0	0.7	0.2	1.0	0.2	21.1	15.6	23.9	29.4
11	1.0	0.0	0.7	0.2	1.0	0.2	21.1	15.6	23.9	29.4
12	1.0	0.0	0.7	0.2	1.0	0.2	21.1	15.6	23.9	29.4
13	0.0	0.0	0.6	0.2	0.9	0.2	21.1	15.6	23.9	29.4
14	1.0	0.0	0.7	0.2	1.0	0.2	21.1	15.6	23.9	29.4
15	1.0	0.0	0.7	0.2	1.0	0.2	21.1	15.6	23.9	29.4
16	1.0	0.0	0.7	0.2	1.0	0.2	21.1	15.6	23.9	29.4
17	1.0	0.0	0.7	0.2	1.0	0.2	21.1	15.6	23.9	29.4
18	0.0	0.0	0.5	0.2	0.5	0.2	21.1	15.6	23.9	29.4
19	0.0	0.0	0.3	0.2	0.2	0.2	21.1	15.6	23.9	29.4
20	0.0	0.0	0.3	0.2	0.2	0.2	15.6	15.6	29.4	29.4
21	0.0	0.0	0.2	0.2	0.2	0.2	15.6	15.6	29.4	29.4
22	0.0	0.0	0.2	0.2	0.2	0.2	15.6	15.6	29.4	29.4
23	0.0	0.0	0.2	0.2	0.2	0.2	15.6	15.6	29.4	29.4
24	0.0	0.0	0.2	0.2	0.2	0.2	15.6	15.6	29.4	29.4

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