

The Challenges in Aligning Environmental and Daylight Performance when Transforming Industrial Buildings into Perimeter Offices

A Quantitative Approach

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Lund University

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

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Abstract

Increased emphasis on sustainable practices and reducing the global warming potential (GWP) kg CO₂ equivalent emissions of buildings and construction processes to mitigate climate change has led to a growing interest in refurbishment and transformation of existing buildings. However, balancing daylight provision with environmental impact targets can be challenging, especially in high-latitude Nordic countries and when industrial buildings are transformed into regularly occupied office spaces. One reason is the potential misalignment between thresholds in the European daylight standard (EN 17037) and national CO₂ limit values. Another reason is the limited availability of daylight hours, which means that large windows are often required to ensure adequate daylighting; however, they can also come at an environmental cost, as they can lead to higher heat loss and increased embodied carbon. Therefore, this study investigated the challenges in managing the alignment of both.

To undertake the investigation, the European daylight standard criteria and national environmental requirements in Nordic countries were reviewed and compared. Denmark was found to have the strictest regulations for both daylight and environmental building performance and was thus chosen as the study's context. Several case studies were assessed for energy and daylight performance by simulating them. The case studies consisted of transforming three industrial formal typologies into office buildings, combined with life cycle assessment (LCA) via multi-objective optimization for varying daylight provision thresholds (minimum, medium, and high), as defined in EN 17037. The three selected formal typologies were a single-story bi-axial building with a sawtooth roof, a multi-story mono-axial building with a barrel roof and ridge skylight, and a multi-story bi-axial building with a flat roof and scattered skylights.

Results seemed to indicate a slight positive trend between GWP emissions and sDA results for low-carbon facade materials and a slight negative trend with carbon-intensive insulation and facade materials due to the difference in whole life carbon between windows and opaque facade walls. However, no issues in aligning daylight provisions with current Danish LCA limits of 12 kgCO₂eq/m²/y were found for both. For upcoming limits (7.5 kgCO₂eq/m²/y), only low-carbon insulation materials complied, and even lower future targets will pose a challenge, especially once the construction process life cycle stages are added.

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Abbreviation

AEC	Architecture, Engineering, and Construction
BB	Barrel Roof Building
BR18	Byggningsreglementet 18, Current Danish Building Regulations
BR25-29	Future Adjustments to Danish Building Regulations in 2025, 2027 and 2029
BR	Building Regulations
CEN	European Committee for Standardization
CIE	Commission Internationale de l'Éclairage
CO₂	Carbon Dioxide
DF	Daylight Factor
EN	European Standard
EPD	Environmental Product Declaration
EUI	Energy Use Intensity
FB	Flat Roof Building
FT	Formal Typology
GWP	Global Warming Potential Total
GFA	Gross Floor Area
GHG	Greenhouse Gases
<i>g</i>-Value	Solar Heat Gain Coefficient
HFA	Heated Floor Area
IES	Illuminating Engineering Society
ISO	International Standard
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCS	Life Cycle Stages
LULUCF	Land Use, Land Use Change and Forestry (Environmental Impact)
MOO	Multi-Objective Optimization
PCR	Product Category Rules
RR(2)	Reduction Roadmap
sDA	Spatial Daylight Autonomy
SB	Sawtooth Roof Building
Tvis	Visual Light Transmittance
TC	European Committee for Standardization Specific Technical Committee
UDI	Useful Daylight Illuminance
UFA	Useful Floor Area
<i>U</i>-Value	Building Element Thermal Transmittance
<i>U_f</i>-Value	Frame Assembly Thermal Transmittance
<i>U_g</i>-Value	Glazing Assembly Thermal Transmittance
<i>U_w</i>-Value	Window Assembly Thermal Transmittance
WID	Well Index Depth
WLC	Whole-life Carbon
WRR	Window to Roof Ratio
WWR	Window to Wall Ratio

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1 Introduction

Globally, buildings and their energy demand occupy 32 % of the global energy demand (UNEP, 2025), resulting in a total of 34 % of kg CO₂ equivalent emissions. Thus, the Architecture, Engineering, and Construction (AEC) sectors significantly contribute to environmental degradation, making AEC a critical industry for reducing carbon emissions and resource consumption. As countries work to align with international agreements, such as the Paris Agreement (UNFCCC, 2018), they are implementing emission limits to decarbonize their energy systems. Consequently, the AEC industry must not only reduce operational energy demands but also address the growing share of embodied carbon emissions. These emissions are linked to the production of materials and construction activities. Such activities are responsible for 18 % of the total global kg CO₂ equivalent emissions (UNEP Key Messages, 2025). In many cases, embodied carbon in low-energy or nearly zero-energy buildings now account for half of a building's life cycle emissions (Chastas et al., 2016; Trinh et al., 2017; WBCSD, 2023).

To design low-energy buildings, reducing their energy demand and heat losses through the building envelope is crucial. Generally, windows exhibit higher heat loss coefficients than opaque facades, which might suggest decreasing window sizes to save energy. Nevertheless, in pursuing optimal environmental performance, one must not overlook other critical building performance criteria like daylighting in buildings. This is especially important in high-latitude Nordic countries and office typologies, where daylight hours are limited, and occupants spend a high fraction of daylight hours indoors. Adequate daylighting has been shown to reduce dependence on electric lighting and enhance health, well-being, and productivity by supporting circadian rhythms, visual comfort, and cognitive performance (Al horr et al., 2016; Chauhan et al., 2023; Rezaei Oghazi, Andersen, et al., 2024). Daylight provision, therefore, is not only an energy-saving strategy but also a human-centered design requirement.

Balancing environmental impacts and daylight provision presents significant challenges, particularly in the *change in use* of existing buildings. As the environmental costs of demolition and new construction come under scrutiny, growing attention is being given to refurbishing and reusing existing building stock (EEA, 2022; Horup et al., 2024). In particular, industrial buildings frequently lend themselves to being transformed as cities grow and city borders with industrial areas move (Vleuten, 1992). However, transforming industrial buildings, which typically show deep plans, into office spaces is challenging as daylight provision can be a key issue (Petković-Grozdanovića et al., 2016).

Addressing the alignment of environmental and daylight performance is not only a design challenge but also a regulatory one, shaped by the building codes that define performance requirements. In Europe, these requirements are often based on technical standards developed by the European Committee for Standardization (CEN-CENELEC), which provides best practice methods for assessing various aspects of building performance. While these standards aim to align practices across EU member states, they are only enforceable when adopted into national building codes. In practice, this adoption varies significantly between countries, leading to discrepancies in regulatory frameworks (Nordic Sustainable Construction, 2025). Furthermore, since standards are developed by different technical committees and at different times, inconsistencies and conflicting methodologies often emerge, making integrated design and performance alignment more difficult.

These challenges become particularly evident in building transformation, where design decisions must balance stricter environmental limits with the need to maintain or improve daylight provision in existing structures. To unpack this challenge, a closer look at the background and interaction of these standards is necessary.

1.1 Background

The CEN-CENELEC consists of technical committees (TCs) responsible for developing standards that provide recommendations, guidance, and frameworks. These standards are used by AEC professionals and are often incorporated into national regulations across EU member states. The aim of these building performance standards is intended to promote comparable and consistent assessments.

Two standards were central for this study. First, the daylight performance standard is the *EN 17037:2018+A1:2021 Daylight in Buildings*, which outlines evaluation methods and recommended performance thresholds for daylight in buildings (CEN, 2021a). Second, the environmental performance standard, *EN 15978:2011 Sustainability of Construction Works – Assessment of Environmental Performance of Buildings – Calculation Method*, defines a standardized approach to Life Cycle Assessment (LCA) for buildings (CEN, 2011).

While these standards provide a technical foundation for much of the AEC industry, the extent to which they are integrated into national regulations varies significantly across Nordic countries. Some countries adopt them as regulatory requirements, while others treat them as voluntary guidelines. This variability can shape how building performance is aligned in practice. This is particularly relevant for Nordic countries such as Denmark, where increasingly ambitious environmental regulations (Nordic Sustainable Construction, 2023) may conflict with daylight requirements aimed at ensuring healthy and attractive indoor environments. These competing demands highlight the need for a more integrated approach to reconcile daylight provision with environmental performance goals.

Achieving such alignment is complex, as strategies that improve daylight access can adversely impact environmental performance, and vice versa. For instance, replacing opaque building envelope elements with glazing can influence embodied carbon depending on the chosen materials. Depending on the materials used for the envelope, this change may either increase or decrease the overall embodied carbon. Furthermore, many buildings utilize internal or external shading devices to ensure visual comfort and mitigate issues such as glare or overheating (Bugenings et al., 2025). Moveable exterior shading devices are commonly chosen for commercial buildings and have been consistently demonstrated to improve energy use as well as visual and thermal comfort (Evola et al., 2017; Yao, 2014). However, these devices are often constructed from carbon-intensive materials, such as aluminum or PVC, which may contribute to an increase in embodied carbon (Dokhanian et al., 2023).

Fenestration components can also greatly influence operational energy in Nordic climates. On the one hand, adding fenestration and increasing daylight levels can reduce the energy demand for electric lighting (Bernett et al., 2021; Chauhan et al., 2023; Rezaei Oghazi, Jusselme, et al., 2024). While Dubois & Flodberg (2013) found that lighting control strategies can save more energy at high latitudes than larger windows; these savings may be of lesser relevance with the introduction of highly efficient LED lighting (Gentile & Dubois, 2017). On the other hand, adding large, glazed surfaces with lower thermal resistance than opaque walls or roofs can increase energy demand for heating due to increased conductive losses and cooling due to increased convective gains (Chauhan et al., 2023; Rezaei Oghazi, Jusselme, et al., 2024; WBCSD, 2023). Even though glazing increases thermal losses during the winter, increased solar gains can offset these losses. Openable windows can also impact the energy demand or the entire need for mechanical ventilation (Rezaei Oghazi, Andersen, et al., 2024).

These trade-offs in the literature led to the interest in examining the interaction between recommended thresholds in EN 17037, boundary conditions, and limit values. The study further assessed how various parameters, environmental limit values, and illuminance thresholds influence and often challenge integrative building performance assessments. The research objective and key research question were then formulated based on research gaps, findings, and advancing knowledge in this field.

1.2 Objective and Research Question

On the building level, this study explored the relationship between recommended daylight provision levels (minimum, medium, and high) of the European daylight performance standard and carbon emission limit values when transforming industrial buildings.

The research centers on transforming three predominant industrial typologies into regularly occupied perimeter office spaces. Geographically, the study is situated in Denmark, where strict and evolving regulations are based on methods in the CEN European standards.

Key Research Question:

What are the key challenges in aligning environmental and daylight requirements when transforming an existing building into perimeter offices across common industrial buildings?

1.3 Limitations

This study is subject to limitations structured according to the main sections of the thesis. The literature review focused primarily on Nordic countries to collect an overview of environmental and daylight performance requirements, thereby narrowing the contextual scope. Language barriers also presented a challenge, as some legislative documents were only available in native languages, requiring manual translation that could introduce interpretation errors.

In the geometrical methodology, simplifications were made to reduce computational demand and maintain consistency across formal typologies (FT). Contextual surroundings were excluded due to the hypothetical nature of the selected FT, which limited the realism of daylight and energy performance simulations. All buildings were also assumed not to have cultural heritage protection; only the ground floor windows on the east and west facades were considered protected. Other performance criteria, like building statics, structural design, moisture safety, hazardous material assessments, fire safety assessments, acoustics, economics, mechanical, plumbing, and electrical (MEP) systems, and renewable energy sources (PVs), were omitted from the scope of this study. Assessing perimeter offices was another limitation, as reaching daylight requirements is easier. By doing this, deeper, less daylit spaces are irregularly occupied and, therefore, excluded from daylight verifications.

The computational methods were comprised whole life cycle carbon (WLC) calculations using LCA, daylighting simulations, and multi-objective optimization. They were developed using methods from Denmark's building regulations (BR18, 2018) framework for performing energy declarations, LCA, and daylighting calculations, which are based on EN standards. The focus on calculation methods defined in the BR18 potentially limits the generalizability of some findings. The LCA was limited by generic or non-case-specific Environmental Product Declarations (EPDs), and system boundaries were not always consistent across materials.

The optimization and data handling processes also had inherent simplifications due to software constraints, especially in aligning daylight and energy simulation engines. These limitations collectively affect the precision and applicability of the results, particularly when attempting to generalize findings or draw conclusions about specific design parameters.

2 Literature Review

The literature review was conducted using scientific databases, libraries, and legislation websites. The database searches were performed on platforms such as ScienceDirect, the Lund University library, Google Scholar, Research Gate, ArODES, and MDPI. Keywords related to daylight provision, limit values, embodied carbon, operational carbon, WLC, LCA, European standards, multi-objective optimization, and environmental regulation were used. After collecting various papers from the database search, the tool Connected Papers helped explore networks of related studies in the fields of daylighting and environmental studies in buildings. Targeted searches were also conducted within Copenhagen municipality's library archives to gather literature on the history of Danish industrial architecture. Examining local and national legislation in Nordic countries was undertaken to understand regulatory frameworks relevant to the study, but the search was limited to daylighting and LCA requirements.

In this study, key terms are defined below to clarify their use in describing environmental performance across life cycle stages (LCS) in various sections of this paper. It is important to note that these definitions can be ambiguous and continue to evolve and encompass varying criteria. CEN standards, the AEC industry, and current literature define the current definitions stated below.

Global Warming Potential (GWP), on a principal level, is an environmental performance metric that quantifies various greenhouse gas (GHG) emissions into a single comparable unit of measure. Examples of GHG are CO₂ (carbon dioxide), CH₄ (methane), N₂O (nitrous oxide), and more (CEN ISO, 2018). In European standards, GWP is described as kg CO₂ equivalent (CEN, 2011).

Embodied Carbon commonly refers to the GWP kg CO₂ equivalent associated with the production (A1-3), construction (A4-5), use (B1-7), and end-of-life stages (C1-4) of a building. The definition excludes B6 (operational energy use) and B7 (operational water use). The D stage is described separately as activities beyond the building life cycle, such as reuse, recovery, and recycling (CEN, 2011, 2021b). The generic definition is “*embodied aspects and impacts over the life cycle*” (CEN, 2021b).

Operational Carbon encompasses the GWP kg CO₂ equivalent resulting from the energy and water operations during the building's use phase, specifically, B6 operational energy use and B7 operational water use. All other LCS stages are excluded from this definition. (CEN, 2011, 2021b). The generic definition is “*operational aspects and impacts during the use stage*” (CEN, 2021b).

Whole Life Carbon (WLC) is not defined by European Standards but is commonly used in the AEC industry. WLC can be defined as the sum of embodied and operational carbon. The D stage was excluded from WLC in this report.

2.1 State of the Art

The backbones of this thesis are the article “Daylight and Carbon Interactions: An Explorative Method to Reconcile Daylight Performance and Carbon Budget Constraints” (Rezaei Oghazi, Jusselme, et al., 2024) and the PhD thesis “An Explorative Method to Support Design Decisions Based on Carbon Constraints and Daylight Sufficiency Needs” (Rezaei Oghazi, Andersen, et al., 2024). These works explore the performance trade-offs between daylight optimization and whole-life carbon (WLC) emissions in residential building facades located in Switzerland. The scope focused on how increasing daylight by glazed fenestration impacts both operational energy and embodied carbon emissions. The optimization assessed 9 000 alternatives, revealing the relationship between spatial daylight autonomy (sDA) and the global warming potential of various structures like concrete, timber, and brick. The method combined parametric optimization modeling with daylight and energy simulations with LCA to establish component-specific carbon budgets focused only on envelope elements. Key findings in this study revealed that an increase in spatial daylight autonomy (sDA) reduces the embodied carbon of resource-intensive materials like concrete and brick. In contrast to low-carbon materials like timber, the result was the opposite. The findings reveal a connection between parameters like glazing area, daylight, operational energy use, and GWP, emphasizing a need to integrate and balance parameters.

Rezaei Oghazi, Andersen, et al. (2024) reviewed daylight and carbon interactions and discovered that, until 2024, 18 studies had investigated this topic. They also found that more studies have been conducted on the interaction of daylight and energy demand or thermal comfort. Besides studies based on field measurements, 95 % utilized simulations, of which 40 % used multi-objective optimizations to investigate the interaction between parameters. Findings on the interaction between daylight provision and WLC vary significantly between different studies. For example, Bernett et al. (2021) established that higher sDA could lead to lower energy demand and decreasing embodied carbon, whereas Chauhan et al. (2023) saw sDA and embodied carbon increase simultaneously.

In their study, Bernett et al. (2021) investigated different FTs, ceiling heights, and structural materials, where ceiling height had the biggest influence on daylight performance and energy use intensity (EUI). Structural materials, however, were the largest contributor to embodied carbon levels.

Contrastingly, Chauhan et al. (2023) found that increasing WWR raised sDA but decreased when fixed shading around the windows was extended. The highest sDA values occurred when the high-rise building had a high form factor and WWR. This increase in sDA led to an increase in EUI but decreased the electrical lighting demand. Due to the facade's design's impact on embodied and operational carbon, a correlation was observed between sDA and embodied carbon. The ideal solution for WLC and sDA of a minimum of 40 % was found to be a form factor ≤ 0.42 and WWR ≥ 30 %. If sDA were to be improved, embodied carbon would consistently increase, even if operational carbon decreased.

Chauhan et al. (2023) also found that WWR was a poor indicator of sDA, which was influenced more by the form factor of the building. This finding contrasts the 10 % rule often utilized by Danish architects and permitted for simple buildings. Here, sufficient daylight can be proven by establishing a glazing area equal to 10 % of the floor area of a room (BR18, 2018, § 379 - § 381).

A case study in the UK (Arup & Saint-Gobain Glass, 2022) found that glass is a primary contributor to WLC in facades, with glass having an 11 % - 20 % impact on the facades embodied carbon and the entire façade adding between 10 % - 20 % to the buildings embodied carbon, depending on its materiality. In the study, glass contributed 26 % - 60 % to the facades' embodied carbon, where replacing glazing after 30 years had a significant impact. They also found that coatings on glass were more effective in reducing WLC than shading systems and blinds, as coatings have an insignificant impact on embodied carbon.

Similarly to Chauhan et al. (2023), Arup and Saint-Gobain Glass (2022) found that embodied carbon can decrease with larger WWR, where operational carbon increases. An interesting finding was that embodied carbon increased when WWR increased from 50 % - 60 %, as windowpanes and frames had to be thicker and thus embodied more CO₂. Furthermore, the study found that larger WWR on west-facing facades decreased WLC emissions, while they increased them on south-facing facades due to higher heat gains and the following cooling demand.

Another study on case-study buildings by Arup & WBCSD (2023) pointed out that even though facades can be said to make up approximately 15 % of the building's embodied carbon, WLC should be employed to inform design decisions. Regarding life cycle stages, Rezaei Oghazi (2024) reflected that life carbon should be broken down into different stages. They also suggest a weighting system, where increased impacts during production and construction should be weighted heavier than operational impacts, as net emission will gradually decrease, and all future impacts are more uncertain, which was also shown by Sørensen Nilsson et al. (2023).

2.2 Justification for Transformation and Adaptive Reuse

Reducing emissions from the construction industry and lowering the environmental impacts of buildings are necessary to maintain Earth's planetary boundaries for continued human future well-being and development (Rockström et al., 2009a). To achieve this, the European Union (EEA, 2022) and researchers (Horup et al., 2024) suggest repurposing existing structures instead of constructing new ones. A recent Danish study investigated whether technological advancements could help reach absolute sustainability targets for the Danish building industry without reducing construction. They found significant exceedances of planetary boundaries and concluded that building activities must be reduced by 80 % from the current rate. This need to decrease new building construction, paired with the Danish population projected to increase by approximately 4 % from 2025 to 2070 (DST, 2025; Horup et al., 2025), underlines the need for reusing existing building stock.

Changing the use of a building by transforming is called *adaptive reuse*, meaning changing a building to meet a new function or need. In contrast, refurbishment improves the building without altering its use. In the case of reconstruction behind existing walls, structural changes, and changes in use, a project can be classified as large-scale adaptation (Douglas, 2006), the type investigated in this study.

Industrial areas are often repurposed as cities expand and their boundaries shift. Denmark has no long history of heavy industry like the UK or its neighbor Germany due to a lack of natural resources and a historical focus on agriculture. Nevertheless, shipyards and machinery production have characterized the biggest Danish cities. The need for production facilities has changed since the 19th and 20th centuries, and the city perimeter, where industrial areas are often located, has moved (Vleuten, 1992). Historically, machines inside industrial buildings and the buildings themselves have gone through changes and become more and more pragmatic, making efficiency and simplification leading design parameters for industrial buildings. Industrial typologies either follow structural systems or design and production sequences, leading to the design of open, flexible spaces to accommodate changes to production line layout or machinery (Viera Renata & Fernando, 2012). This internal openness and flexibility thus make them ideal shells for interior floors and rooms that can be added.

Another reason for targeting industrial buildings is that the average age at demolition for commercial buildings in Denmark is only 60 years. If the demolished building was built after 1990, it is typically only 41 years old when demolished. This contrasts residential buildings, which are often over 100 years old at the time of demolition (Andersen & Negendahl, 2023). These findings stress the importance of investigating reusing buildings if their primary use is found obsolete after a comparably short time.

2.3 Environmental Performance Standards and Regulations

The technical committees, TC 169 (Light and Lighting) and TC 350 (Sustainability of Construction Works) have, over time, developed their standards independently, each operating strictly within its own scope (CEN-CENELEC, 2025a). Although a liaison has recently been established to encourage collaboration between these two committees, no concrete evidence of active coordination or integration was found (Email exchange A, personal communication, 2025). The lack of collaboration is illustrated in Figure 1, which maps the relationships between relevant standards and highlights their degree of integration. The standards central to this study are outlined in green. This disconnect is relevant, as it underscores one of the key challenges addressed in the research: the outdated alignment between daylight and environmental performance frameworks at the standard level.

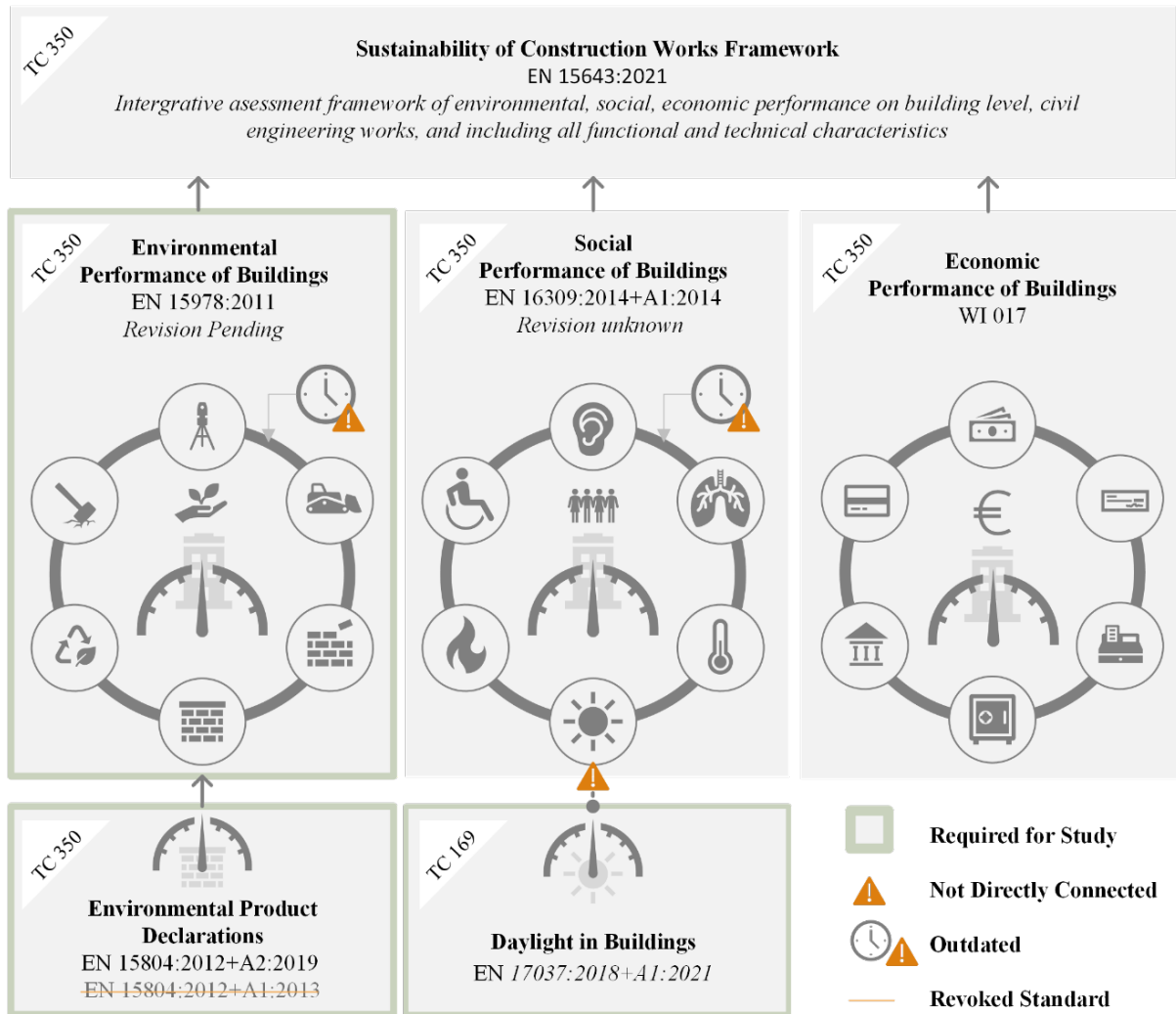


Figure 1: Overview of sustainability standards adapted from CEN 350 (2021)

The *EN 15804:2012+A2:2019 Sustainability of construction works – Environmental product declarations* section 3.15 of CEN 350 (2019) defines LCA as "A compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle." This is the latest standard that sets core guidelines that define a set of product category rules (PCR) for Type 3 environmental product declarations (EPDs) of construction products or services, such as insulation products. The PCR rules ensure that the reporting of environmental impacts is valid, standardized, and comparable between similar products. These EPDs can be used in *EN 15978:2011* (CEN 350, 2011) but must be valid and based on EN 15804. A critical note is that there are two versions of EN 15804, in which the calculation of the widely used environmental impact indicator category

GWP changed from *EN 15804:2012+A1:2013* (CEN, 2013) (see Figure 1, yellow line) to *EN 15804:2012+A2:2019*. The newer version splits GWP into three distinct categories, GWP-fossil, GWP-biogenic, GWP-LULUC, and their aggregate GWP-total, whereas the older one only gives one value for GWP, not distinguishing between GWP from biogenic or fossil sources. This increases the comparison difficulty between EPDs of similar products, as EPDs are often valid for up to five years, and thus, valid EPDs in 2025 may be based on this revoked standard.

The EN 15978 (see Figure 1) provides guidance on the scope and system boundaries for the assessment to then use for evaluation of various environmental impacts across building relevant life cycle stages (LCS). This standard currently uses GWP, not GWP-Total. Since 2021, it has been discussed to create a new version, which aligns with the new versions of EN 15804 and *EN 15643:2021 Sustainability of construction works – Framework for assessment of buildings and civil engineering works* CEN 350 (2021) standards. However, as of 2025, only unofficial drafts exist (Pasanen, 2024).

The TC 350 has created the *EN 16309:2014+A1:2014 Sustainability of Construction Works - Evaluation of the Social Performance of Buildings - Calculation Methodology* to assess social aspects like acoustics, fire, thermal comfort, and more (Figure 1). The standard defines daylight as social performance and attempts to bridge LCA with daylight criteria (CEN, 2014). The content has not been updated since 2014 and has not been developed with TC 169 (CEN, 2017b). The TC 350 did, however, mention older methods from TC 169, like daylight factor (DF), a static daylight metric to indicate daylight quality, but due to the publishing date, dynamic, climate-based metrics or recommended thresholds in EN 17037 are not included. These inconsistencies can create challenges when trying to integrate daylight performance into the environmental performance according to this standard.

Table 1 shows an overview of building regulations in Iceland, Norway, Denmark, Sweden, and Finland to determine the LCA status and how strict the environmental performance regulations are in these Nordic countries. The data was sourced from *Harmonized Carbon Limit Values for Buildings in Nordic Countries*, published in 2024. The report was created by Nordic Sustainable Construction, which is run by the Nordic Council of Ministers. All data listed in this 2024 report was quality-checked by comparing the report findings with current building regulations as of March 2025.

Table 1: Nordic overview of LCA implementation adapted from Nordic Sustainable Construction Report (2024)

	Denmark	Finland	Iceland	Norway	Sweden
Regulatory Body	BR18	Rakennuslaki	HMS	TEK17	Boverket
Implementation	2023 (Active)	2025 (Active)	2024 (Active)	2023 (Active)	2022 (Active)
Standards Utilized	EN 15978:2011 EN 15804:2012 +A2:2019	EN 15978:2011 EN 15804:2012 +A2:2019	EN ISO 14040 EN ISO 14044 EN 15804:2012 +A2:2019	EN 15978:2011 NS 3720:2018 EN 15804:2012 +A2:2019	EN 15978:2011 EN 15804:2012 +A2:2019
Reference Unit	kgCO ₂ eq./m ² /y (A _{ref} and HFA) 50 years	kgCO ₂ eq./m ² /y (HFA) 50 years	kgCO ₂ eq./m ² /y (HFA) 50 years	kgCO ₂ eq./m ² /y (GFA) 50 years	kgCO ₂ eq /m ² (GFA) 50 years
Limit Values	12 8 – voluntary class 2023	14 2024 in Helsinki	None	None	None
Building Types Included	All buildings above 1000m ² , except holiday homes + renovation	All buildings, except, Single family + holiday homes, industry, other, renovation	All buildings, except holiday homes	All buildings, except Single- family homes	All buildings above 100m ² except industrial
Expected Revisions	Limits vary by building type and min. 1000 m ² removed in July 2025	No revisions expected	Expected Limit by 2028	No expected limits	Limits vary by building type July 2025

<i>Included LCS</i>	<i>Denmark</i>	<i>Finland</i>	<i>Iceland</i>	<i>Norway</i>	<i>Sweden</i>
<i>A0 Pre-Construction</i>	Not included in the current version of EN 15978:2011 standard.				
<i>A1 – A3 Production Stages</i>	Yes	Yes	Yes	Yes	Yes
<i>A4 Transport to Site</i>	Yes, July 2025	Yes	Yes	Yes	Yes
<i>A5 Construction works</i>	Yes, July 2025	Yes	No	Yes	Yes
<i>B1 Use in Building</i>	No	No	No	No	No
<i>B2 Maintenance</i>	No	No	No	Yes	Yes, July 2025
<i>B3 Repairs</i>	No	No	No	No	No
<i>B4 Replacement</i>	Yes	Yes	Yes	No	Yes
<i>B5 Refurbishment</i>	No	No	No	No	No
<i>B6 Operational Energy Use</i>	Yes	Yes	Yes	No	Yes, July 2025
<i>B7 Operational Water Use</i>	No	No	No	No	No
<i>B8 User Activities</i>	Not included in the current version of EN 15978:2011 standard.				
<i>C1 Demolition Works</i>	No	Yes	Yes	No	Yes, July 2025
<i>C2 Transport</i>	No	Yes	Yes	No	Yes, July 2025
<i>C3 Waste Management</i>	Yes	Yes	Yes	No	Yes, July 2025
<i>C4 Final Disposal</i>	Yes	Yes	Yes	No	Yes, July 2025
<i>D1 Recovery, Reuse, Recycle, Potential</i>	Yes, Documented independently	Yes, Documented independently	Yes, Documented independently	No	No
<i>D2 Exported Utilities potential</i>	Not included in the current version of EN 15978:2011 standard.				

Regarding Table 1, **Denmark** began LCA in 2023 and was the Nordic country to set limit values for buildings above 1000 m², with some exceptions (BR18, 2018). The assessment method follows the European standard (BR18, 2018). A revision will occur in July 2025. The new limit value will decrease for all building types, and LCS will be added. Revisions will happen again in 2027 and 2029 (Nordic Sustainable Construction, 2024). Since January 2024, reused building materials have been calculated as 0 kgCO₂eq./m²/y (BR18, 2018). The climate declaration is reported once the building is constructed. Regarding previously mentioned differences between the two versions of EN 15804, which can lead to discrepancies between EPDs for similar products, Danish regulations allow the use of both, according to BR18 § 250 - § 298, 1.6 (2018), as EPDs are valid for five years after their publishing date, even though impacts are calculated differently.

Finland has required LCA for all buildings since 2025, including extensive renovations (Finlex, 2024). The regulations make exceptions for some building projects. The Finnish Ministry of the Environment defines the assessment method and follows the European standard. The limit now in force is for multi-story residential buildings (*Finland Carbon Footprint Limit Value*, 2024).

Iceland has required LCA since 2024. As of September 1, 2025, HMS requires most new buildings to be assessed (1321/2021 – Regulation on the (11th) amendment to the Building Regulation, No.

112/2012.) The assessment is based on EN ISO 14040 and EN ISO 14044. These ISO standards were developed before the European standard and provide broader guidelines without a specific sectoral focus (Pallas, 2021). There are no required limit values, and HMS aims to incorporate limit values into building regulations by 2027 or 2028 (HMS Life Cycle Assessment, 2025).

Norway has required LCA since 2023 for multi-family homes and commercial buildings, extensive renovations, and changes in use. The assessment follows the NS 3720:2018 standard, based on the European standard (§17-1. Greenhouse Gas Accounts from Materials, 2023). As of January 2025, TEK17 has not set limit values for buildings in Norway.

Sweden was the first country to require mandatory climate declarations, though without limit values, in 2022. This assessment includes new buildings and only the production LCS. This regulation did not apply to single-family housing or buildings below 1000 m². By 2025, *Boverket* will require building limit values. In 2027, more LCS must be included (Boverket Climate Declarations, 2024).

The legislative review of current and future LCA requirements reveals that boundary conditions differ significantly between Nordic countries, making cross-country comparisons challenging because of the LCS and the functional unit (Nordic Sustainable Construction, 2025). The Energy Performance of Building Directive (EPBD) would like to take steps to align countries to use the same functional unit area of useful floor area (UFA) instead, the discussion is still ongoing (Energy Performance of Buildings (Recast) Amendments Adopted by the European Parliament, 2024).

2.3.1 Future Developments in Denmark

As Denmark was found to have the strictest limit values, further research was conducted into the near future. Permittable limit values for multi-story buildings and offices will be reduced to 7.5 kgCO₂eq./m²/y in 2025 (BR25), 6.8 kgCO₂eq./m²/y in 2027 (BR27), and 6.2 kgCO₂eq./m²/y in 2029 (BR29) (Nordic Sustainable Construction, 2024). Furthermore, from July 2025 onwards, the building process, LCS A4 and A5 must be included in the LCA and fall below a limit of 1.5 kgCO₂eq./m²/y (Social- og Boligministeriet, 2024).

The Reduction Roadmap is an initiative by the Danish AEC industry to lower limit values to align with the Paris Agreement (UNFCCC, 2018) and the Planetary Boundary for Climate Change (Rockström et al., 2009b; Steffen et al., 2015) with industry-specific CO₂ reduction targets, covering more than 90 % of new construction projects in Denmark. As of March 2025, 630 Danish AEC companies support the Reduction Roadmap. The Reduction Roadmap is a tool for companies and universities to urge building regulations to tighten environmental impact regulations now to extend carbon budgets for the next 7 – 12 years. Tighter regulations would require projects to reduce carbon emissions, whereas the current regulations allow “business as usual,” meaning that only projects with above-average climate goals, often meaning budgets, meet lower environmental impacts than the average building. The RR2 specifies annual reductions in the Danish construction industry's environmental impact and CO₂ emissions to meet the maximum 1.5 °C global warming, calculated based on IPCC scenarios (IPCC, 2018). This translates these maximum impacts to building LCA results and orders them by the likelihood of achieving the Paris Agreement (Reduction Roadmap, 2024).

- 5.8 kgCO₂eq./m²/y = 50 % likelihood
- 3.8 kgCO₂eq./m²/y = 67 % likelihood
- 2.5 kgCO₂eq./m²/y = 83 % likelihood

The initiative argues that the limit should be the maximum allowed LCA results in the building regulations. The RR2 also mentioned that limits should differ for different building functions allocating, for example, 4.5 kgCO₂eq./m²/y to residential buildings. In contrast, offices and institutions could embody up to 7 kgCO₂eq./m²/y, with sports, cultural, and health facilities not having any limit (Reduction Roadmap, 2024).

2.4 Daylight Performance Standard and Regulation

The European standard EN 17037:2018+A1:2021, titled *Daylight in Buildings*, was developed by the TC 169 committee and was first approved on the 29th of July 2018. The standard provides the frameworks to quantify the daylight performance in buildings with regularly occupied spaces. According to the standard, daylight quality is divided into four chapters: Daylight Provision, View-out, Sunlight Exposure, and Glare. Each chapter describes how to calculate the various metrics.

Daylight provision can be calculated using static or dynamic methods (CEN 169, 2021, 5.1.3). The static method employs the daylight factor approach, which includes recommended daylight factor values tailored to the geographic location of the CEN member state. These are linked to standard indoor illuminance reference levels of 100, 300, 500, and 750 lux. sDA is a dynamic daylight metric method, which is a climate-based daylight metric that evaluates illuminance levels throughout the year.

The standard provides sDA daylight provision threshold values for different fenestration openings, such as vertical, inclined, and horizontal. The thresholds for vertical and inclined are grouped into three levels: “*Minimum, medium, and high*”. Each level specifies a target illuminance (E_T) and a minimum (E_{TM}) value. For example, both the E_T and E_{TM} threshold values must be satisfied for the specified fraction of daylight hours to reach the high level. In the horizontal openings table, only “*minimum, medium, and high*” levels for minimum illuminance values (E_{TM}) are recommended (Table 2).

Table 2: Daylight provision – target and minimum target illuminance. Adapted from (CEN, 2021a)

Levels	Target illuminance (E_T lx)	Fraction of space for target level (F_{plane}, %)	Minimum target illuminance (E_{TM} lx)	Fraction of space for minimum target level (F_{plane}, %)	Fraction of daylight hours (F_{time}, %)
Minimum	300 E_T lx	50 %	100 E_{TM} lx	95 %	50 %
Medium	500 E_T lx	50 %	300 E_{TM} lx	95 %	50 %
High	750 E_T lx	50 %	500 E_{TM} lx	95 %	50 %

CEN-CENELEC lists countries that are CEN members. This includes all Nordic countries, including Iceland, Norway, Sweden, Denmark, and Finland. Each country has chosen to incorporate or reference the standard in various ways.

Denmark partially integrates the standards recommendations for illuminance into the building regulations. According to § 379 of BR18 (2018), a minimum of “300 lux for 50 % of the relevant floor area for at least half of the daylight hours” is the legally binding threshold (■, Table 2). For simple buildings, static daylight metric methods like the glass-to-floor area method, also known as the 10 % rule or daylight factor, can be used. Denmark also documents daylight performance in the regulatory project phase. Daylighting methods must be clearly stated in a daylight report and submitted before the building is completed. Daylight is not verified after construction is completed.

In contrast, Sweden references the standard as a supplement calculation to the other daylight performance verification methods (*Dagsljus*, 2022); the Swedish Work Environment Authority refers to EN 17307 as an example method to verify daylight quality in work environments (Arbetsmiljöverket, 2025). Iceland (Byggingarreglugerð, 10.4. Birta Og Lýsing, 2020) and Norway (§ 13-7. Lys, 2017) follow a similar method but reference the standard called 12464-1:2021, one specific to indoor workplace electric light and lighting. Finland does not heavily regulate daylight (*FINLEX*® - *Säädökset alkuperäisinä*, 2017). Over the years, concerns have been raised that new buildings lack adequate daylighting (Varis, 2022). Even though EN 17037 is the national standard, it is not referenced in regulations, which is similar to other Nordic countries.

The article *Towards a Wider Adoption of EN 17037: A Scandinavian Perspective* (Rogers et al., 2025) expands the discussion of daylight regulations by exploring the challenges and limitations that have prevented the implementation of EN 17037 across all Scandinavian countries. The paper touches on multiple challenges, such as problems meeting the minimum recommended illuminance threshold ($300 E_T \text{ lx for } F_{\text{time}}, 50 \%$) in the standard, implementing dynamic daylight metrics like spatial daylight autonomy (sDA), regulatory constraints, and industry opposition, specifically in Nordic countries.

The opposition to adopting minimum, medium, and high daylight thresholds is due to the high latitude of Nordic countries and the common occurrence of overcast skies. These conditions make it difficult to meet high illuminance levels like 750 lux and, in many cases, even the minimum levels of 300 lux, particularly for residential buildings (Jin et al., 2025).

The paper concludes that the TC 169 committee, responsible for the standard, should revisit the recommended daylight metrics, specifically the minimum level, to ensure high-latitude countries can reach these levels within reasonable design options.

3 Methodology

The process was broken down into three main steps to answer the research question and find challenges connected to aligning environmental and daylight performance (Figure 2). The first step was contextually framing the study. The geographical context was chosen based on the previous literature review, and FT geometry and transformation strategies were developed here. The second step included data collection for specific design parameters and their characteristics and inputs, as well as setting for the following simulations. Lastly, three case study buildings were simulated via computational modeling for daylight and environmental performance in the third step.

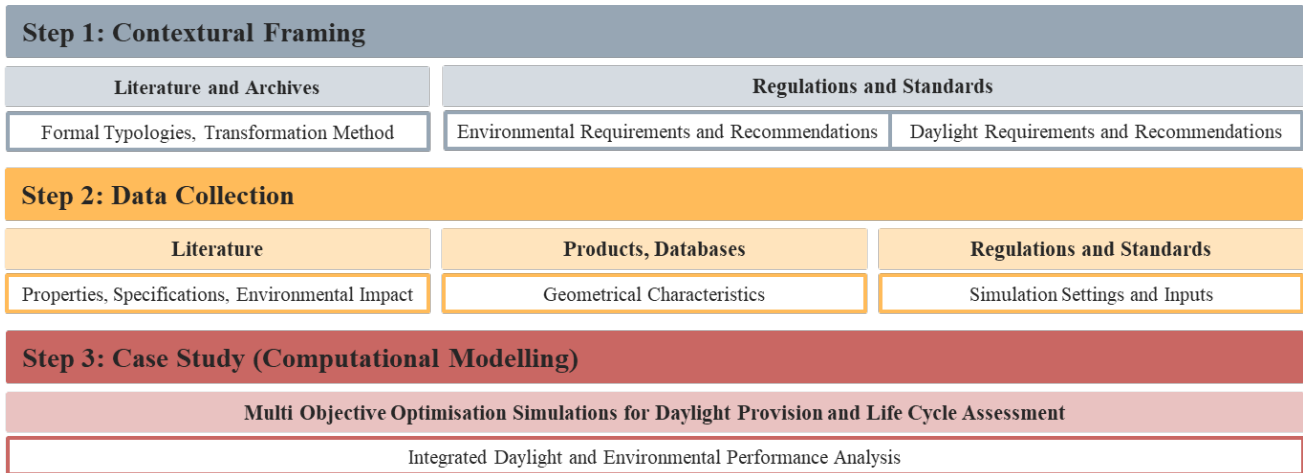


Figure 2: Three Step Research Process

3.1 Contextual Justification

Based on a review of LCA and the environmental impact requirements in Nordic countries, it was found that Denmark had the strictest requirements. Therefore, to interpret the results of the LCAs and see how environmental performance and daylight provision interact, results will be assessed according to the following limit values (Table 3):

Table 3: LCA limit values for assessment

	Value Origin	kgCO ₂ eq/m ² /y	Reference
Danish Building Regulations	Current (BR18) LCA limit	12.0	(BR18, 2018; Social- og Boligministeriet, 2024)
	BR25 LCA limit	7.5	
	BR27 LCA limit	6.8	
	BR29 LCA limit	6.2	
Reduction Roadmap	RR2 50% likelihood	5.8	(Reduction Roadmap, 2024)

Denmark was chosen as the basis for this daylight study because the Danish building regulations are the only national guidelines that directly reference the minimum illuminance and daylight factor values outlined in the European daylight standard, as discussed in Section 2.3. For Danish regulations, meeting minimum E_T thresholds is sufficient (Table 2).

However, the method of this study investigated the challenge of meeting minimum, medium, and high thresholds across occupied areas of each FT. It is important to note that, to meet these daylight performance levels in EN 17037, both the target illuminance (E_T) and the minimum target illuminance (E_{TM}) must be achieved for at least 50 % of the daylight hours (F_{time} ≥ 50%).

3.2 Architectural Concept

The initial concept focused on buildings on the island of *Refshaleøen* in Copenhagen, Denmark. This former industrial area features multiple long, rectangular buildings (see Figure 3) with primarily east and west-oriented side lighting and ridge skylights, which are former welding buildings (Steenberg & Hacksen Kampmann, 2019).




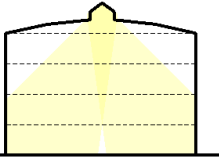
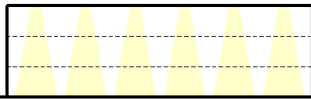
Figure 3: Aerial photo of characteristic welding buildings on Refshaleøen (Google Earth, 2025)

This area was considered because of an idea competition in early 2024 to find transformation plans for the entire city district. The master plan competition will be held in 2025 (*Konkurrencer*, 2024). However, instead of focusing on a single location, the concept followed a broader approach by examining multiple formal typologies. All typologies were analyzed on a conceptual open site in Copenhagen without including any specific urban context in the assessments.

3.2.1 Formal Typologies

Common industrial formal typologies (FT) were found by scrutinizing a book about industrial architecture in Denmark (Birket-Smith & Mikkelsen, 2010), a document and website with building overviews by the Danish Agency for Culture and Palaces (Birket-Smith, 2007; *Industrihistoriens Danmarkskort*, 2024), Denmark's national encyclopedia (Danmarks Nationalleksikon, 2022) and satellite images (*Google Earth*, 2025). As daylighting is a central issue when transforming buildings (Petković-Grozdanovića et al., 2016), it was decided to find three typologies with different top lighting systems, floor plate depths, and heights (Table 4). Each FT was originally a single-story building with varied ceiling heights. Varying numbers of new floors can be added based on the height when the building is transformed. This study will refer to the three identified typologies by their roof shape. There are the sawtooth roof building (SB), barrel roof building (BB), and flat roof building (FB).

Table 4: Formal Typology (FT). Types SB, BB, and FB

<i>Sawtooth Roof (SB)</i>	<i>Barrel Roof (BB)</i>	<i>Flat Roof (FB)</i>
		
<ul style="list-style-type: none"> • North oriented skylights • Deep floor plate • Feasible to add one floor 	<ul style="list-style-type: none"> • Ridge skylight • Shallow floor plate • Feasible to add three floors 	<ul style="list-style-type: none"> • Scattered skylights • Medium floor plate • Feasible to add two floors

A study by Lepel (2006) was also used to identify and categorize buildings. As per the study, it is possible to divide industrial formal typologies into six distinct types, distinguished by height and depth. The following three types have been matched to the different FTs found when scrutinizing buildings in Denmark (Figure 4).

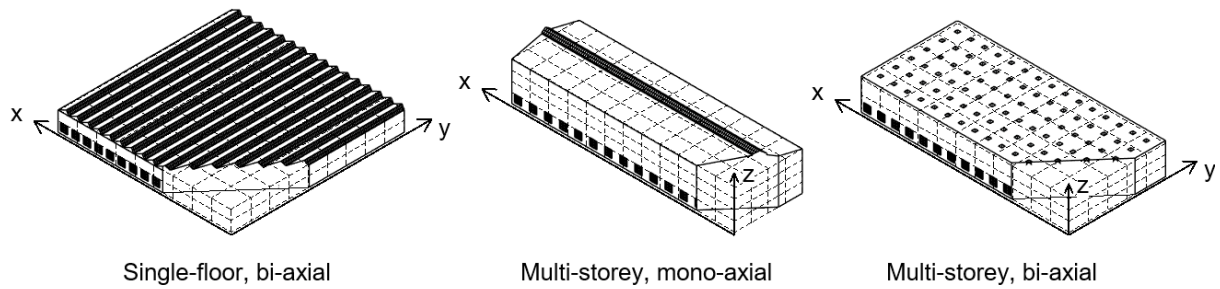


Figure 4: Building formal typologies. Adapted from Lepel (2006)

Based on these approaches found in the literature, the three SB, BB, and FB formal typologies were chosen. All buildings investigated are shown in Table 37, Appendix A. Furthermore, Figure 35, Figure 36, and Figure 37 show images of the investigated referenced buildings. One interesting example, shown in Figure 5, was *Gabriel Ervervspark* (former *Kjærs Mølle Fabrik*) in Aalborg, a former cloth factory, where all three identified formal typologies were connected as one building (Krak, 1910).



Figure 5: *Gabriel Ervervspark* (former *Kjærs Mølle Fabrik*). Image taken from Google Earth (2025).

SB, the single-floor, biaxial building with a sawtooth roof: These buildings' original function was either the production of heavy items, like trains, or meat processing, which all required wide floor plates and little height. North-oriented sawtooth roofs often provide light, as these allow for covering large areas and provide uniform natural daylight (Dubois et al., 2019; Neufert & Neufert, 2000).

BB, the multi-story, mono-axial building with a barrel roof and ridge skylight, is tall and has narrow floor plates. Spinning and welding buildings needed to be tall rather than especially wide. The buildings are covered with barrel roofs, which, due to their rounded structure, can cover large spans without needing much structural material. Long skylights with east-west orientation are added to the roof's ridge to provide daylight to those long buildings (Steenberg & Hacksen Kampmann, 2019).

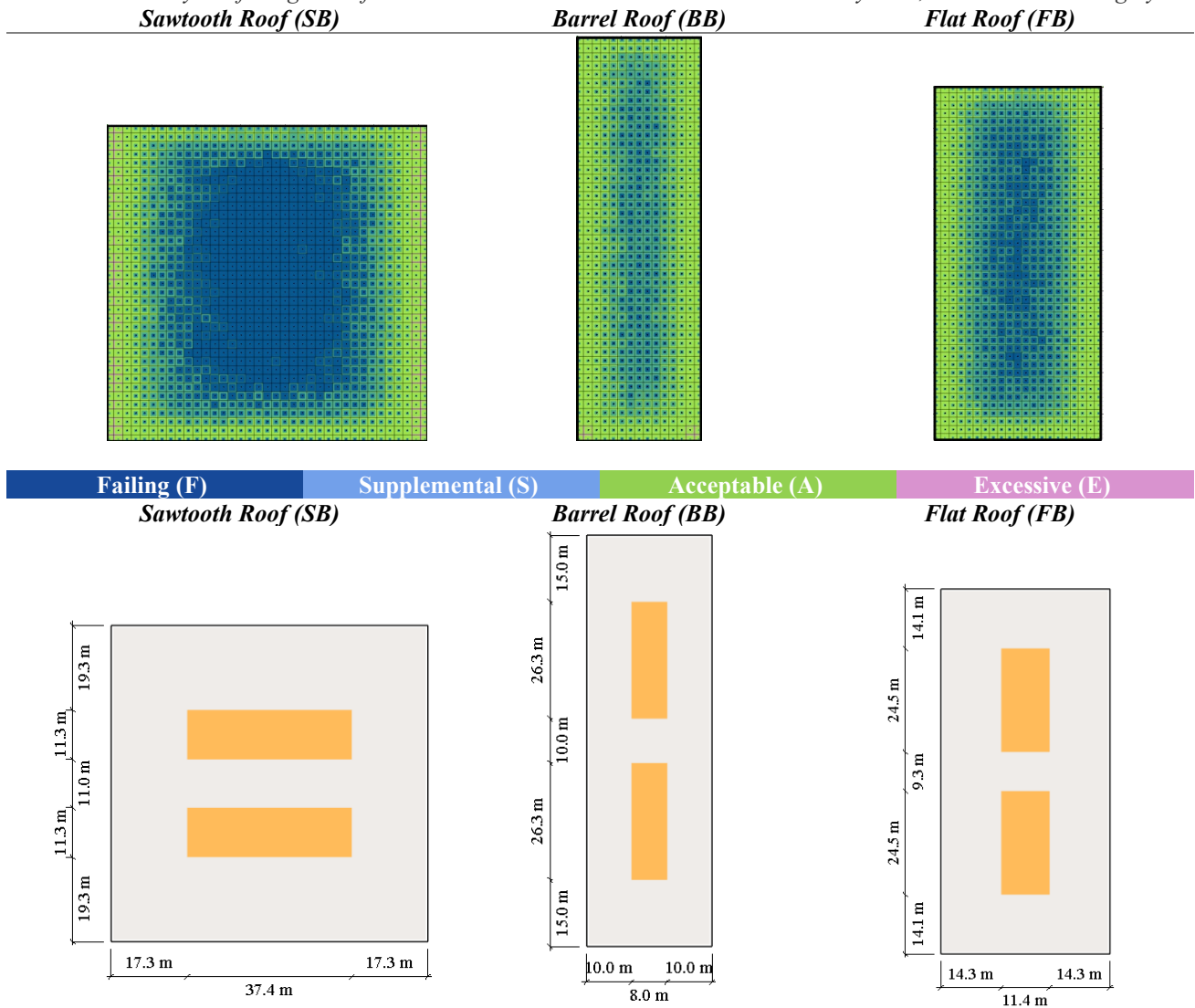
FB is a multi-story, bi-axial building with a flat roof or low-pitch roof and flat scattered skylights. These buildings come in all heights. They gained popularity after electrical lighting became the norm and daylight was no longer a requirement. In these cases, skylights can still provide daylight or smoke ventilation openings (Birket-Smith & Mikkelsen, 2010).

Building drawings from an archive (Københavns Kommune, 2024) sized the multi-story monoaxial BB. The other types, SB and FB, followed the concept established by Lepel (2006) to create deeper floor plates and different heights while maintaining the floor area of the example building. When determining floor levels, a ceiling height of 4 m was set for each level for all FTs. The top floor varied due to the top lighting and roof shapes.

A pre-assessment using Useful Daylight Illuminance (UDI) was performed with and without floors to place the atria in each FT. This analysis revealed uniform illumination in all three buildings when no new floors were added. After introducing new levels to each FT, it was decided to add the atria in the central areas with low daylight illuminance (Table 6). Two atria were placed in each FT.

Based on the beforementioned review of atrium-to-HFA ratios and UDI analysis for the ground floors, the atria principle chosen was an area equal to 20 % of the total floor area (Table 7). The atria were enclosed instead of open to the outside to keep the architectural characteristics of the existing typologies. Enclosed atria are furthermore ideal for temperate climates (Lechner & Andrasik, 2022, p. 16).

Table 6: UDI analysis of the ground floor with all levels added. The atria are shown in yellow, and other areas in grey.



The decision to centralize the atria was based on literature that found such a central atria design compared to other atria types, like an atrium sharing a portion of the façade, does not substantially impact energy performance (Erlendsson, 2014). In centralized atria, the primary light source comes from top lighting, where, for example, a fully glazed atrium was best to illuminate the atrium and the adjacent spaces (Li et al., 2019).

3.2.3.1 Calculated Atria Properties

To describe the atria's geometry, the rectangular well index depth (WID) was used (Eq. 1).

$$WID = \frac{y(w+l)}{2wl} \quad (1)$$

In the formula, y is the height, w is the width, and l is the length of the atrium. The vertical daylight factor adjacent to the atrium decreases with increased well index (Du & Sharples, 2011); thus, shallower atria provide more daylight to adjoining spaces.

A hypothesis was that the atria in the SB would have a larger impact on daylight levels in the occupied areas than on the BB. However, the SB has the deepest floor plate; thus, the lower well index might contribute to achieving daylight levels similar to the narrower floor plate in the BB and FB.

A study found that atrium shape and volume strongly affect heating and cooling loads, with rectangular atria often performing worse than square ones (Aldawoud, 2013). Table 7 shows the geometric properties of all atria in each FT, where atria form factor and WID serve as quick indicators of EUI and daylight performance.

Table 7: Atrium properties

Atria Quantities	Sawtooth Roof (SB)	Barrel Roof (BB)	Flat Roof (FB)
HFA (Ground Floor)	840 m ² (Fl. 0)	420 m ² (Fl. 0)	560 m ² (Fl. 0)
Area Across All Levels	1680 m ² (Fl. 0 – 1)	1680 m ² (Fl. 0 – 3)	1680 m ² (Fl. 0 – 2)
Atria Area to Building HFA	20 %	20 %	20 %
Volume / m³	6660 m ³	7650 m ³	6730 m ³
WID per Atrium	0.5	1.6	0.8
Atria Form Factor	4.1	5.95	6.78

3.2.4 Calculated Building Heat Loss Form Factor

The form factor of each FT was calculated to gain insights into performance criteria like operational energy use. This geometry data was used to interpret the results. An overview of the envelope areas and the calculated form factors is provided in Table 8.

Buildings with a lower form factor have a smaller envelope area per square meter of HFA, which leads to the common hypothesis that they have less heat loss through the envelope (assuming similar U -values) and, thus, higher energy efficiency (Wei et al., 2016). According to the calculations, the most compact is FB, followed by BB and SB.

Table 8: Form factor of each formal typology

	Sawtooth Roof (SB)	Barrel Roof (BB)	Flat Roof (FB)
Envelope Area	8926.8 m ²	6513.0 m ²	6489.6 m ²
HFA	9526.5 m ²	9106.2 m ²	9245.8 m ²
Form Factor	0.94	0.72	0.70

3.3 Design Parameter Overview

A parametric analysis was performed to investigate the relationship between different design choices. Three categories, facades, placement, and materials, amounted to 23 varied parameters, as shown in Table 9 and Figure 6. This resulted in a total of 3 456 possible design combinations per FT.

Table 9: Overview of varied parameters

Parameter Categories	Parameter Description	Variations
Envelope (Section 3.3.1)		
Facade thickness and LCA impact	Wood fiber insulation façade system	2
	Phenolic foam insulation façade system	
Fenestration Geometry (Sections 3.3.2 and 3.3.4)		
Side lighting – WWR (including existing openings)	20 %	4
	30 %	
	40 %	
	60 %	
Top lighting – percentage of existing glazing (including existing openings, looking at if better closed)	Formal typology (FT) only	3
	FT + 100 % atrium glazing	
	100 % atrium glazing only	
Materials (Sections 3.3.3 and 3.3.5)		
Glazing type (side lighting)	3-layers, LowE (<i>SKN154, solrude</i>)	3
	3-layers, Standard (<i>Standard rude</i>)	
	2-layers, Double Glazing (<i>Edge</i>)	
Glazing type existing (side lighting)	1+2 layers, Double Glazing (<i>Edge</i>)	3
	1+2 layers, Double Glazing (<i>Bøjsø</i>)	
	1+3 layers, Standard (<i>Standard rude</i>)	
Glazing type (top lighting)	2-layers, Clear (T Clear Double)	4
	2-layers, Solar (T Sun Double)	
	3-layers, Clear (T Clear Triple)	
	3-layers, Solar (T Sun Triple)	
Window frame material (side lighting)	Aluminum	4
	Hybrid (wood and aluminum)	
	PVC	
	Wood	

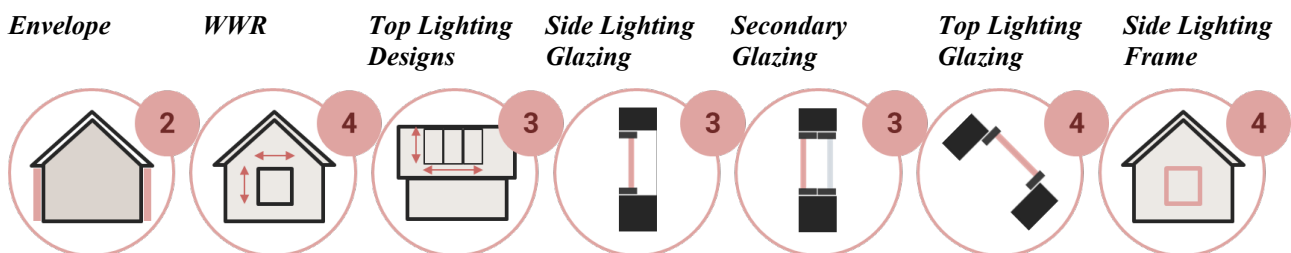


Figure 6: Visual overview of varied parameters and number of variations per category

The assessment also consisted of fixed parameters that were not optimized in the simulation. Roofs, top and side roller blinds, demolition works, and top lighting frame parameters were fixed. However, the quantities of the elements varied based on the window-to-wall ratio (WWR), window-to-roof ratio (WRR), and formal typology. Interior glazed and opaque walls, stairs, doors, flooring, ceilings, decks, columns/beams were fixed, but areas and quantities varied by formal typology. Outdoor areas and pavement, water installations, heating installations, and ventilation installations were fixed to the same quantity for all FTs. These not-varying quantities were logged in Excel.

3.3.1 Envelope Materials and Constructions

Existing constructions were assumed to be the same in all buildings, with facades consisting of 200 mm of concrete. Though probably unrealistic, this limitation was made to simplify the study, as all investigated buildings differed in façade materiality, mainly between brick or concrete (Figure 7). However, archive drawings were investigated for all examples of all FT types, and they were found to have a structural column and beam system, making facades non-bearing and thus thinner. The assumption was further supported by a site visit to *Refshaleøen*, where both materials were found as thin facades. It was decided not to do the same for the other FTs due to time constraints and to investigate the impact of building form rather than materiality.

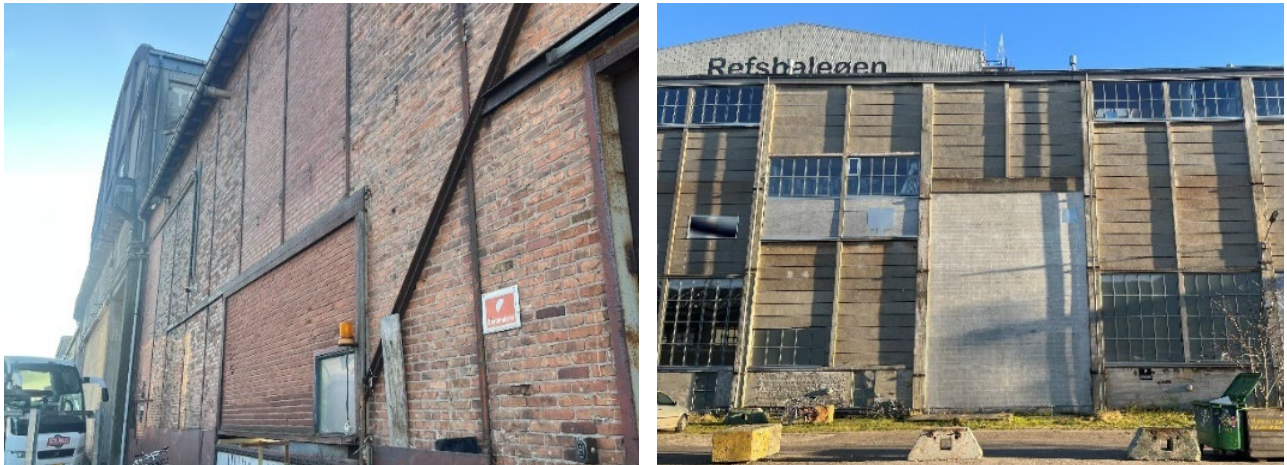


Figure 7: Facade materiality on Refshaleøen, Copenhagen.

The existing roof, consisting of plywood and bitumen roofing, was considered uninsulated. It was assumed that the existing roof construction would be removed and new cassettes added. This was based on findings from a site visit on *Refshaleøen*. One building currently being used for storage (*B&W market*) was visually investigated, and moisture damage was found on the existing roof. Other findings were damage on the top glazing (Figure 8). These findings matched those by Steenberg & Hacksen Kampmann (2019), who did a case study on another building in the same area.

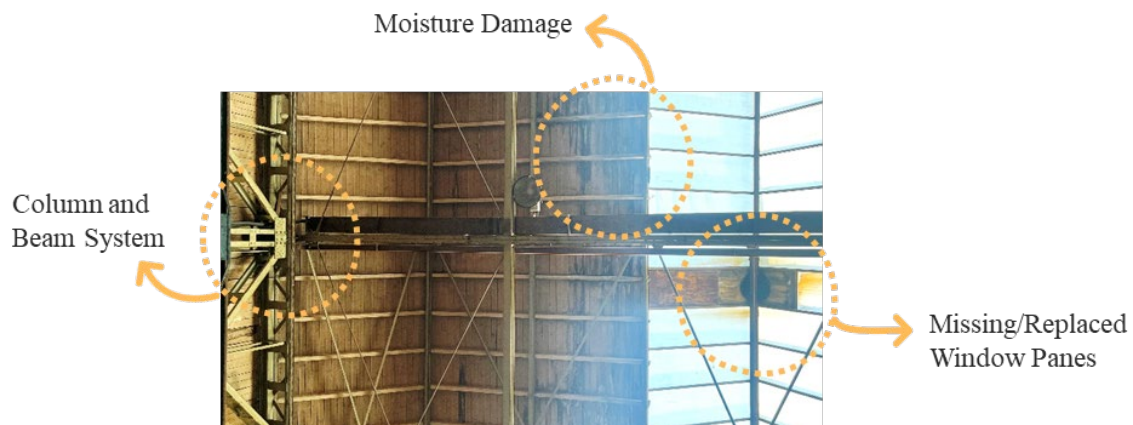


Figure 8: Roof and Ridge Skylight in B&W market on Refshaleøen, Copenhagen.

The existing wall constructions were insulated to achieve the minimum U -value requirements (BR18, 2018). The insulation and cladding types were varied with different thicknesses and environmental impacts to investigate the effect of fixed shading on daylight provision.

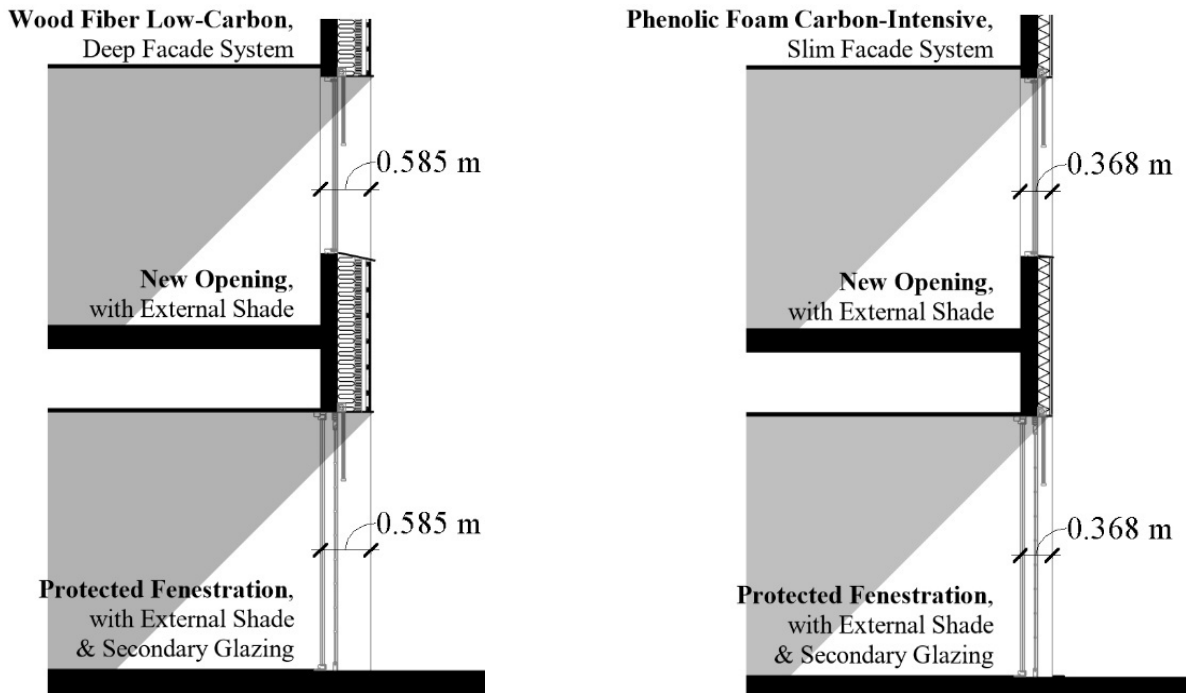


Figure 9: Envelope Parameter Variations, Facade Type, and Thickness. Wood Fiber (Left) & Phenolic Foam (Right)

On the right in Figure 9, wood-fiber batts and burnt wood cladding (OkoTomrerer, 2023) are shown. This system had greater shading and a lower GWP. The phenolic foam and aluminum cladding system was a slim system with a high GWP. All constructions (Table 10) were calculated in *Ubakus.de* (Plag, 2024), which performs thermal resistance calculations after *ISO 6946* (2017) to calculate *U*-values and corresponding thicknesses for constructions that reach *U*-value requirements in the BR18 (2018)

Table 10: Construction types and specifications, diagram outputs from *Ubakus.de*

Construction	Properties and Layers (from inside to outside)																																								
Wood Fiber Façade	<table border="1"> <thead> <tr> <th>#</th> <th>Material</th> <th>λ [W/mK]</th> <th>R [m²K/W]</th> </tr> </thead> <tbody> <tr> <td></td> <td>Thermal contact resistance*</td> <td></td> <td>0,130</td> </tr> <tr> <td>1</td> <td>20 cm Concrete</td> <td>2,000</td> <td>0,100</td> </tr> <tr> <td>2</td> <td>28 cm Biofib Trio</td> <td>0,038</td> <td>7,368</td> </tr> <tr> <td></td> <td>28 cm Spruce (7,0%)</td> <td>0,130</td> <td>2,154</td> </tr> <tr> <td></td> <td>Thermal contact resistance*</td> <td></td> <td>0,130</td> </tr> <tr> <td>3</td> <td>2,5 cm Rear ventilated level (outside air)</td> <td></td> <td></td> </tr> <tr> <td>4</td> <td>3 cm Rear ventilated level (outside air)</td> <td></td> <td></td> </tr> <tr> <td>5</td> <td>5 cm Spruce</td> <td></td> <td></td> </tr> <tr> <td></td> <td>58,5 cm Whole component</td> <td></td> <td>6,691</td> </tr> </tbody> </table> <p style="text-align: right;">U-value = 0.15 W/(m²K)</p>	#	Material	λ [W/mK]	R [m ² K/W]		Thermal contact resistance*		0,130	1	20 cm Concrete	2,000	0,100	2	28 cm Biofib Trio	0,038	7,368		28 cm Spruce (7,0%)	0,130	2,154		Thermal contact resistance*		0,130	3	2,5 cm Rear ventilated level (outside air)			4	3 cm Rear ventilated level (outside air)			5	5 cm Spruce				58,5 cm Whole component		6,691
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	36,8 cm Whole component		6,713																																						

Roof		#	Material	λ [W/mK]	R [m ² K/W]	
			Thermal contact resistance*		0,100	
		1	4,5 cm Knauf Insulation Mineral Plus HB 034	0,035	1,286	
			4,5 cm Spruce (7,0%)	0,130	0,346	
		2	0,05 cm Vapor barrier sd=100m	0,220	0,002	
		3	30 cm Knauf Insulation Mineral Plus HB 034	0,035	8,571	
			30 cm Spruce (7,0%)	0,130	2,308	
	Thermal contact resistance*			0,100		
4	4,5 cm Rear ventilated level (outside air)					
5	1,2 cm Plywood					
6	1 cm Bitumen (Membran/Bahn)					
		41,25 cm	Whole component		8,535	
					U-value = 0.12 W/(m²K)	
Existing Ground Slab		#	Material	λ [W/mK]	R [m ² K/W]	
			Thermal contact resistance*		0,170	
		1	15 cm Concrete	2,000	0,075	
		2	34 cm ROCKWOOL Formrock 035	0,035	9,714	
			Thermal contact resistance*			0,040
			49 cm	Whole component		9,999
					U-value = 0.10 W/(m²K)	

3.3.2 Side Lighting Geometry

Existing side lighting was sized and placed according to building archive drawings for the BB (Københavns Kommune, 2024). All FTs had a total of 135 m² existing windows in the east and west facades on the ground floor (Figure 10). The existing WWR for each FT was 38 % for FB, 36 % for BB, and 47 % for SB. The highest WWR in the varied parameter list was 60 %. New windows were established between existing ones to reach this for all facades. The WWR supplement was 22 % for FB, 24 % for BB, and 13 % for SB. This supplement was only applied at 60 % WWR.

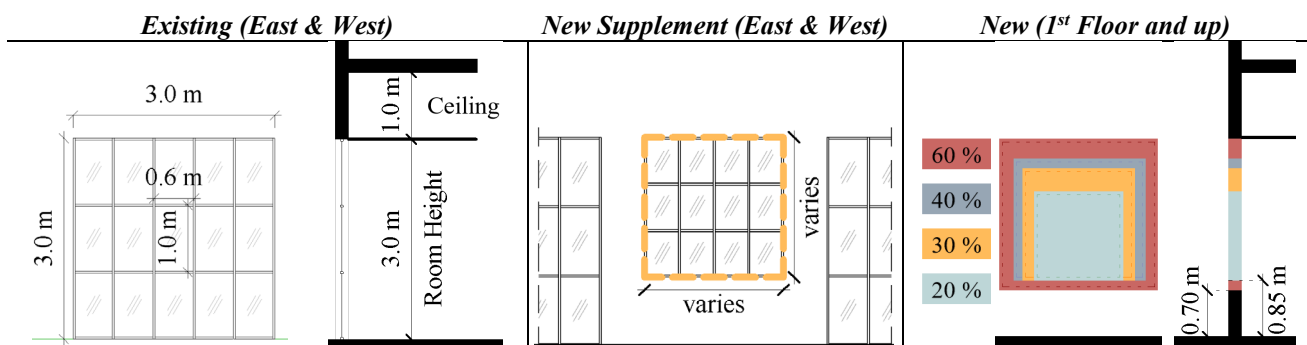


Figure 10: Existing (left) and new (right) side lighting geometry principles. Elevation (left) and section (right).

Window shapes and placements impact daylight performance. It was decided to investigate nearly square windows with a sill height of around 80 cm, which with a 5 cm window frame would mean that window glazing starts at the same height as the daylight analysis grid. This ensures that larger WWR first generates taller but higher-placed windows before generating windows that extend below the 80 cm sill height. This decision was based on a study in Sweden that found that square windows and high middle placements perform best for sDA and UDI analysis (Vogiatzi, 2018).

Numerous studies that investigated the impact of WWR on daylighting and WWR per orientation determined the size of windows. Using DF, Danish researchers identified optimal ratios between 20 % and 35 % (Christoffersen & Johnsen, 1999). Similarly, a study identified WWR between 20 % and 40 % as ideal for offices in Sweden and Canada (Dubois et al., 2019, p. 264). A Swedish study found that the DF only marginally increased after 60 % WWR (Buelow-Huebe, 2008). Thus, the WWR for this study was decided to vary between 20 %, 30 %, 40 %, and 60 %.

Ideally, WWR should differ for different cardinal orientations, with north-facing windows being larger than those towards the other directions (Dubois et al., 2019, p. 264). However, to limit the study, it was decided that the WWR would not vary per orientation.

3.3.3 Side Lighting Materials

Existing windows were assumed to be iron wrath frames with single glazing, based on the reference buildings for the barrel roof. The specifications included can be seen in Table 11. The included pane was set to 3 mm *Pilkington Optifloat Clear (Pilkington Spectrum, 2025)*.

Table 11: Glazing existing window

Window		g_g-Value (%)	U_g-value ($W/(m^2K)$)	T_{vis} (%)	LR_{out} (%)	LR_{in} (%)
Existing	1-layer, Existing windows	89	5.78	91	8	8

To transform the building into an office, new windows must be added, and secondary glazing and frames must be added to the existing windows to improve energy performance. The decision to keep existing windows instead of replacing them was taken from an architectural perspective. The old window glazing was assumed to equal the reference buildings found on *Refshaleøen*. Here, glazing showed uneven reflections (Figure 11), which is common in old panes due to different production methods that were less precise than modern float glass production (Berenjian & Whittleston, 2017). Additionally, the glass had a greenish-blue tint due to high iron levels (Varshneya & Mauro, 2019). Both properties are highly characteristic of older buildings, and it was decided to keep the windows to relate to the FTs industrial heritage.

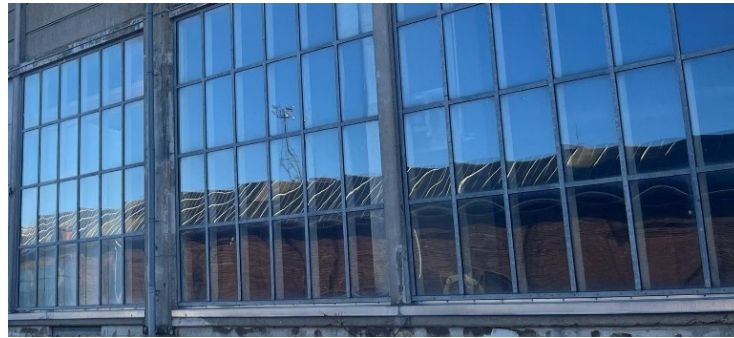


Figure 11: Window glass on Refshaleøen showing uneven reflections.

To ensure that tested window assembly solutions were realistically available on the Danish market, they were based on actual products by Velfac for side lighting and Velux for top lighting, both Danish manufacturers. To streamline assembly specifications and environmental impacts, assemblies with the specifications provided by the manufacturers were built in Pilkington Spectrum, a tool that lets professionals build their own glazing assemblies. However, the tool will disallow assemblies that are “*unwise or impractical*” (Pilkington Spectrum, 2025). Here, the *Spec-it* function was used to find assemblies that matched technical specifications (Pilkington, 2024). Assemblies are shown in Appendix A, Figure 39 through Figure 48.

Table 12: Glazing types. All new side lighting is based on VELFAC (2025), except for assembly marked *, which is based on Bøjsø døre og vinduer A/S (2025)

Window		g_g-Value (%)	U_g-value ($W/(m^2K)$)	T_{vis} (%)	LR_{out} (%)	LR_{in} (%)	Energy Class
New Side Lighting	3-layers, LowE (<i>SKN154, solrude</i>)	26	0.52	47	17	28	A
	3-layers, Standard (<i>Standard rude</i>)	53	0.52	74	14	14	A
	2-layers, Double Glazing (<i>Edge</i>)	79	2.62	82	15	15	B
New Secondary Side Lighting	1+2 layers, Double Glazing (<i>Edge</i>)	73	1.70	76	21	21	B
	1+2 layers, Double Glazing (<i>Bøjsø</i>)*	69	1.22	71	23	23	A
	1+3 layers, Standard (<i>Standard rude</i>)	68	0.47	68	20	19	A

In Table 12, window materials are varied. Double pane windows were assessed to determine the impact compared to triple pane windows and other construction types. However, the Danish building regulations only allow windows with an energy class A to be used in buildings occupied all year (BR18, 2018). These energy class A windows have an energy balance value of 0 or below 0, meaning more energy is gained than lost through the window. Research of Danish window manufacturers found that only triple-pane windows fulfill this requirement, whereas double-pane windows generally have energy class B, which may be used in holiday homes or listed buildings. Double-pane windows were included in the study to investigate if the regulation is reasonable.

It was challenging to find window frame specifications, like U_f -values, separate from the glazing, as manufacturers generally provided U -values for the total window assembly and glazing but not for frames. Because of this, properties for the frames were sourced from *EN ISO 10077-2:2017 Thermal performance of windows, doors, and shutters – Calculation of thermal transmittance – Part 2: Numerical method for frames* CEN 89 (2017). Utilizing the standard instead of market products is one of the study’s limitations. Thermal transmittances of frames from the standard were found to be too high when the energy balance of the windows was calculated based on glazing specifications by the manufacturers and linear transmittances and U_f -values from the standard. Window frame depths and widths did not vary with increasing window sizes, further limiting the study. Window frames for siding lighting are outlined in Table 13.

Table 13: Window frame specifications, based on EN ISO 10077-2:2017 (CEN, 2017a)

Material	Width (m)	Depth (m)	U_f -value (W/m ² K)
Aluminum	0.065	0.063	3.22
Hybrid	0.090	0.120	1.44
PVC	0.068	0.083	2.07
Wood	0.063	0.083	1.36

3.3.4 Top Lighting Geometry

A review of roof fenestration systems (Sharples & Lash, 2007) found that performance greatly differs based on the location of a building, research method, and studied daylight conditions, and it is thus not possible to give a general recommendation for which roof fenestration systems would perform best.

The SB typology (Figure 12) can have different angles, such as placing glazing at a 90 ° angle or sloped (Lechner & Andrasik, 2022; Neufert & Neufert, 2000). Reference buildings investigated featured both (Table 37, appendix A). However, Dubois et al. (2019, p. 304) speculate that sloped systems with reflectors in the Nordics might be the most beneficial for collecting zenithal light and sun at low solar altitudes. Therefore, it was decided to include angled sawtooth top lighting in this study.

The BB top lighting was based on a Copenhagen drawing archive. Top lighting sizes and angles were taken from the archive drawings (Københavns Kommune, 2024).

The FB typology top lighting was initially determined by a rule of thumb by spacing 1.0 to 1.5 times the ceiling height (Mahone Group, 2014). Due to the FT heights, a considerable distance between skylights resulted in a significantly smaller glazing area than in other typologies. Instead, an aerial assessment of various FB typologies using Google Earth (Figure 39) revealed that the spacing was 40 % – 50 % more condensed than the rule of thumb. A condensed array was chosen.

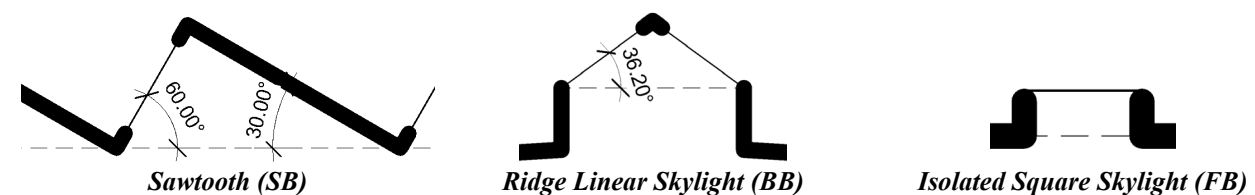
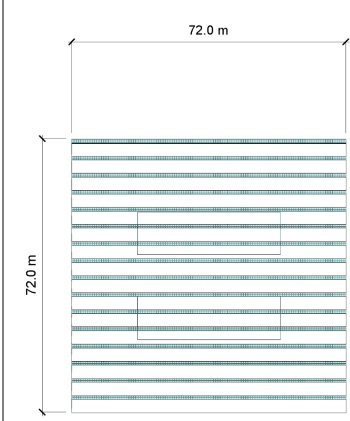
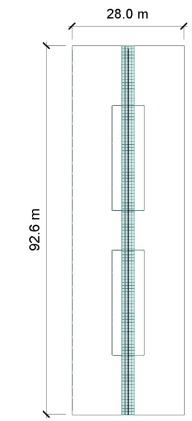
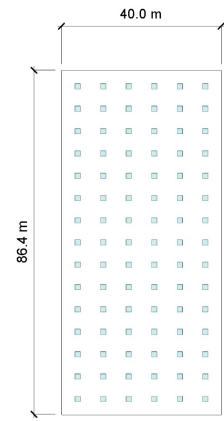
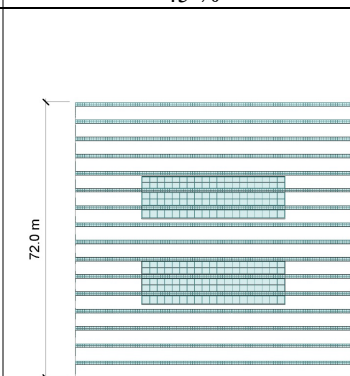
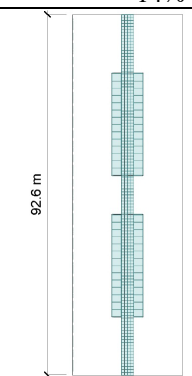
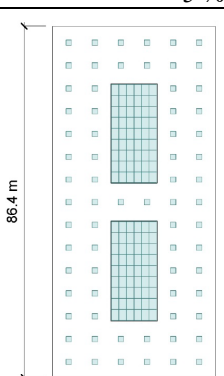
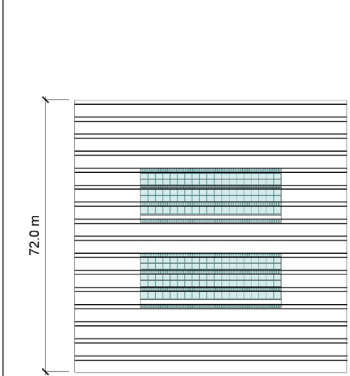
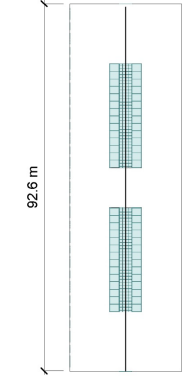
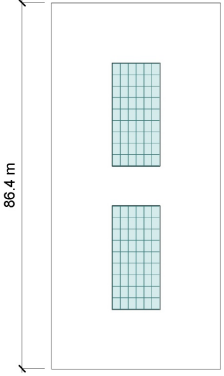


Figure 12: Top lighting types

Table 14 represents the roof design variations with WRR. *Design Variation 1* was determined based on the FT described in Section 3.2. *Design Variation 2* assessed the impact of the existing layout for each FT with a fully glazed atrium. *Design Variation 3* examined only the effect of a fully glazed atrium. These options were chosen based on the literature.

Table 14: Roof plan design variations for each formal typology (FT)

	Sawtooth Roof (SB)	Barrel Roof (BB)	Flat Roof (FB)
Design Variation 1: <i>Base geometry only</i>			
WRR	45 %	14%	5 %
Design Variation 2: <i>Base Geometry + 100% atrium glazing</i>			
WRR	72 %	27 %	24 %
Design Variation 3: <i>100% atrium glazing only</i>			
WRR	34 %	19 %	18 %

3.3.5 Top Lighting Materials

Based on the NEEA (2015) findings and an email exchange (Email exchange B, personal communication, 2025), there were concerns about moisture, maintenance, and safety risks of adding secondary glazing to existing top lighting. There was also little evidence of this being done in practice. A decision was made to establish new top lighting. Four new glazing options were investigated: two double-glazing options and two triple-glazing options, one with higher visual transmittances and one with a lower solar heat gain coefficient (g-value) (Table 15).

Table 15: Glazing types. All new top lighting is based on Velux products (VELUX Danmark A/S & Artelia A/S, 2023); the product name is mentioned in brackets

Window	g_g -value (%)	U_g -value ($W/(m^2K)$)	T_{vis} (%)	LR_{out} (%)	LR_{in} (%)
2-layers, Clear (T Clear Double)	61	1.1	80	11	11
2-layers, LowE (T Sun Double)	28	1.1	51	19	18
3-layers, Clear (T Clear Triple)	52	0.6	72	14	14
3-layers, LowE (T Sun Triple)	24	0.6	46	20	21

Window frames for top lighting are assumed to be aluminum for all glazing design options, as there was not enough data available for large, glazed roof areas constructed in wooden or plastic frames. These window materials were only available for residential use cases (Velux, 2025).

3.4 Computational Method

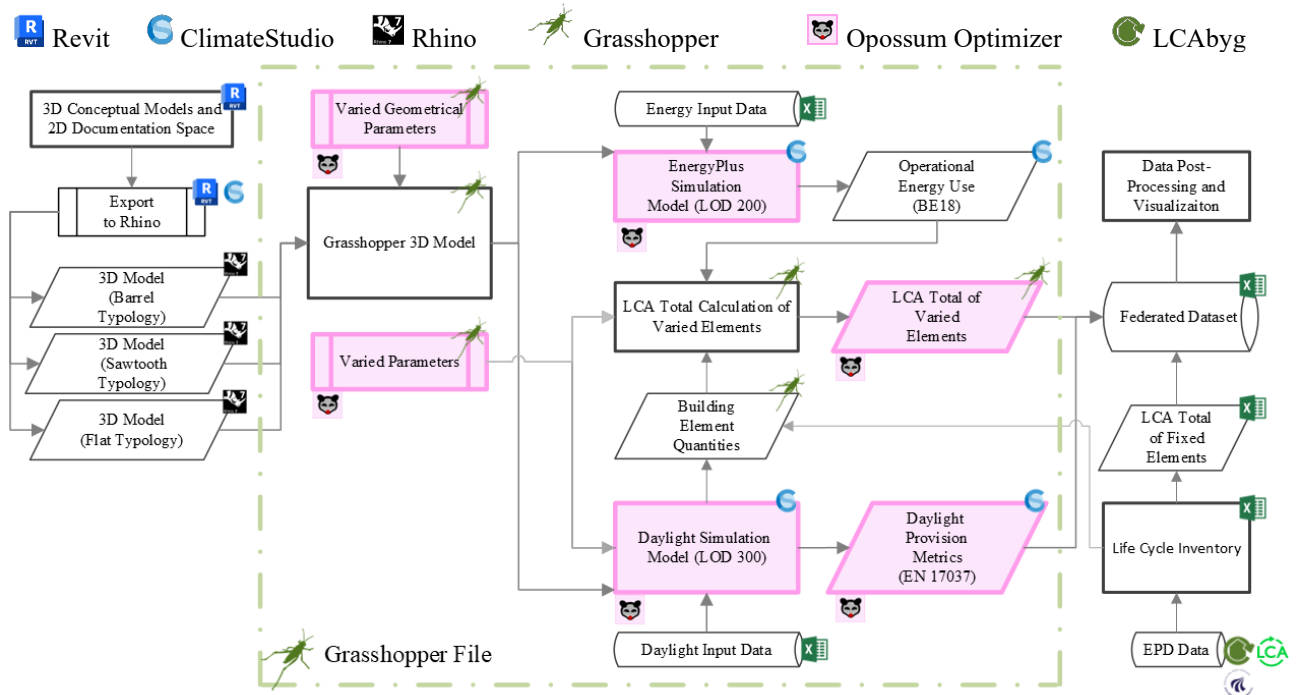


Figure 13: Computational workflow diagram and software

The process began in the *Revit 2024* Autodesk (2024) model, where the conceptual phase defined the geometrical concept (Figure 13). All models were centrally stored in Revit, which also served as a 2D documentation space for drawing documentation, like plans, sections, and diagrams.

The three FT 3D models were exported from *Revit 2024* to *Rhino 7* by Robert McNeel (2020) using the *Climate Studio Version 2.0* by Solemma (2024) exporter plug-in for *Revit*. In *Rhino 7*, the 3D models were assigned to a standardized layer structure consistent across all FT. The decision to orient the BB and FB typologies with their short sides northward was based on the SB Top lighting, which was assumed to be oriented towards the north to capture diffuse daylight (Section 3.1.1). This orientation also reduced 3D modeling time by minimizing the number of Rhino layers.

The geometry was linked to *Grasshopper Version 7.38.24338.17001* Robert McNeel (2020a) by geometry pipelines, and some were internalized to limit the number of pipelines. Varied materials, properties, and geometric parameters were listed in a panel and connected to a list item, where a slider selected the item in the list. The data lists were connected to the *Climate Studio* daylight and *Climate Studio Energy Plus (E+)* Simulations, the Grasshopper LCA calculation for varied building elements, and geometry. The same Copenhagen weather file (Mostapha, 2021) was used for simulations. Data

required for simulations and LCA calculations was collected in *LCAbyg 2023.3 Version 5.4.0.5* Aalborg University Copenhagen (2024), *OneClick LCA for Denmark, Trial for BR18 & DGNB DK* (One Click LCA Ltd., 2024), and from references, stored in Microsoft Excel, and then included in the calculation using Grasshopper. The LCA total of fixed building elements was stored externally in Excel and added to the simulated LCA parts in post-processing.

Opossum 3.1.1 Institute for Computational Design, University of Stuttgart (2024) was used as the optimization solver. The component was connected to all sliders (variables), simulators (energy and daylight models), and the optimization objective data, including the LCA total of varied building elements and daylight performance metrics. All data was logged in Excel using the *TT Toolbox* grasshopper plug-in (*CORE Studio*, 2025).

3.4.1 Whole Life Carbon Calculations

3.4.1.1 LCA Framework

The framework for LCA is defined by EN 15978:2011 (CEN, 2011), starting with identifying the goal and then specifying its scope and what to include. The scope includes functional units, reference study periods, and system boundaries.

First, the goal of the LCA for each FT was to find whether ideal parameter configurations for daylight performance would comply with LCA limit values, as required by the Danish building regulations (BR18, 2018). The life cycle assessment (LCA) was performed according to the Danish building regulations BR18. The methodical framework behind the regulations is based on EN 15978:2011, *Sustainability in building and construction – Assessment of the environmental quality of buildings – Calculation method* (CEN, 2011).

Second, the scope of the LCA, all building elements required for LCA as stated in BR18 (2018) § 297 - § 298, Appendix 1.4. These elements were foundations, terrain decks, exterior and interior walls, floor slabs, ceiling and floor finishes, roofs, stairs and ramps, columns and beams, balconies, windows, doors, glass facades, water and HVAC installations, electricity production and transport (for example elevators), mechanical installations, and outdoor areas. Secondary joints, mounting, and fastening systems were excluded if not part of the primary structural system. As the FTs are transformation projects, foundations,

terrain decks, and exterior structural walls were excluded, as they were part of the existing building. Furthermore, the buildings had no balconies, so those were also omitted.

Third, the functional unit: The environmental impact category must be global warming potential (GWP) (BR18, 2018; CEN, 2011). GWP is commonly used because it has the highest impact compared to other environmental impact categories, which can, for example, be seen in the weighting system created by JRC (Sala et al., 2018). The functional unit for the LCA in Denmark is kg CO₂-equivalents per m² per year (kgCO₂eq / m² / y). The calculated area assessed must be the building's A_{ref} and heated floor area (A_{HFA}). The LCA is performed for a reference study period of 50 years (BR18, 2018, § 297).

Fourth, regarding system boundaries, LCA is performed for cradle-to-gate with options, module C3-C4, and module D. This means that GWP impact was determined for the life cycle stages A1 - A3 (product stage), B4 and B6 (use stage), and C3 - C4 (end-of-life stage). The D stage (benefits) must be stated separately and is not included in compliance calculations (BR18, 2018). In June 2025, the rules will change to include A4 and A5 stages. However, these stages were excluded due to the exclusion of context and site in this study and the goal of generalizing the data.

According to § 297 (BR18, 2018), reference values from BR18 or EPDs based on EN 15804 must be utilized to calculate the environmental impact of different materials. The total environmental impact of a building is calculated according to (Eq. 2):

$$GWP = \left(\frac{A1+A2+A3+B4+C3+C4}{A_{ref} \times 50 \text{ years}} \right) + \left(\frac{B6}{A_{HFA} \times 50 \text{ years}} \right) \quad (2)$$

Where A_{ref} is the total floor area, including walk-on ceilings, and 25 % of the exterior carports and ramp areas, calculated according to § 297 of the BR18 (2018) in this study, A_{ref} was assumed to be equal to A_{HFA} .

3.4.1.2 Life Cycle Inventory

The initial idea was to simplify the LCI by utilizing generic reference values based on the FTs HFA (Nielsen et al., 2022; Tozan et al., 2021) for as many building parts as possible. These generic values are based on data from 60 Danish buildings, and the reports offer median and lower-quartile values (Table 16).

Table 16: Environmental impact of fixed building parts. Impact in GWP, [kg CO₂eq/ m² (HFA) / y (50 years)] (Nielsen et al., 2022; Tozan et al., 2021) and (BR18, 2018)

	Building Elements	Mean Reference	Low Reference
Internals	Decks	1.35E+00	6.90E-01
	Columns / Beams	1.03E-01	4.80E-02
	Interior Walls (other)	4.93E-01	3.10E-01
	Stairs	4.90E-02	2.00E-02
	Doors	5.30E-02	1.80E-02
	Flooring	6.50E-01	6.50E-01
	Ceilings	4.50E-01	4.50E-01
Install-ations	Water installations	9.50E-02	1.90E-02
	Heating installations	2.40E-02	3.00E-03
	Vent. Installations	5.70E-02	2.20E-02

However, some areas and quantities for building parts differed vastly between the three FTs. HFA-based impacts, thus, do not show the difference. Therefore, quantity-based (area, length, count) impacts were tested for fixed elements. Impacts for this were taken from LCAByg (Aalborg University Copenhagen, 2024). Generic EPD data in LCAByg is based on Danish generic values that include a 10 % contingency for safety and are based on industry EPDs and the German database *Ökobau* (Kragh & Birgisdottir, 2023; *ÖKOBAUDAT*, 2025). The EPDs included technical descriptions of building parts and complied with EN 15804:2012+A1:2013 (CEN, 2013). The refurbished protected glazing on the east and west facades was set to 0 kgCO₂eq./m²/y as stated in section 3.3.2.

Table 17: Environmental impact of fixed building parts in GWP, [kg CO₂ eq / m² (construction) / y (50 years)]. Building parts marked with * are in GWP in kgCO₂eq / floor / year. Source LCAByg (Aalborg University Copenhagen, 2024) .

	Building Part	Total	A1-3	B4	C3	C4
Internals	Decks	1.79E-01	-8.19E-01	0.00E+00	9.97E-01	7.59E-04
	Parquet Flooring	1.56E-01	-2.74E-01	0.00E+00	4.29E-01	0.00E+00
	Ceilings	2.20E-01	1.08E-01	1.10E-01	1.27E-03	6.61E-04
	Interior Glazed Wall (Atrium)	2.45E+00	1.25E+00	1.17E+00	8.16E-03	2.21E-02
	Interior Walls (opaque)	2.14E-01	-1.31E-01	0.00E+00	3.36E-01	8.87E-03
	Interior Walls (glazed)	1.48E+00	7.60E-01	6.99E-01	8.16E-03	2.21E-02
	Stairs (two timber stairs and two concrete escape stairs per floor)*	3.00E+01	1.27E+01	0.00E+00	1.73E+01	0.00E+00
Ext.	Demolition Existing Roof	1.20E-02	0.00E+00	0.00E+00	1.17E-02	3.27E-04
	Demolition Existing top lighting	6.96E-01	0.00E+00	0.00E+00	6.96E-01	0.00E+00
	Terrain (pavement surrounding the buildings)	6.47E-01	3.11E-01	3.23E-01	6.79E-03	5.01E-03

Columns were estimated to be placed approximately every 8 m and connected with beams on which the wooden decks would be placed. The column height was set to 4 m. As all buildings had various levels added, the SB would have 1680 m of columns and beams, the BB would have 1800 m, and the FB would have 1670 m. As for the environmental impact, a generic value for columns and beams was chosen (Nielsen et al., 2022), shown in Table 18.

Table 18: Environmental impact columns and beams. Impact in GWP, [kg CO₂ eq / m (material) / y (50 years)] Reference Value taken from Nielsen et al. (2022).

Building Elements	Total
Columns and Beams	2.35E+01

A sensitivity analysis was then performed to test the influence of data certainty and the level of detail of LCI data. Here, the GWP for fixed elements was calculated in four different combinations. The first two combination tests utilized all reference values shown in Table 16, one with mean reference values, so average building materials, and one with low reference values. Both tests calculated GWP based on the HFA of the FT. The other two tests included impact values from LCAByg based on the material unit. Impacts for outdoor terrain areas were specific in all tests, as no HFA-based reference values were found. Furthermore, all tests kept water, heating, and ventilation installations as HFA-based generic impacts. Generic values for columns and beams were utilized as well; however, they were already unit-based.

Building parts that were varied in the simulation, included the new roof, façade insulations, fenestration glazing, window frames, and shading and blinds.

The facades of the existing buildings must be fitted with adequate insulation to live up to the *U*-value regulations from the building regulations. For this, two solutions were investigated in the LCA: a thin assembly with phenolic foam insulation and aluminum cladding and a thicker assembly with rigid wood fiber insulation and burnt wood cladding. The A1-3 stages for the phenolic foam (Kingspan, 2021) and burnt wood (Okotomrerer, 2023) were taken from product EPDs via *OneClick LCA* (One Click LCA Ltd., 2024), as no fitting EPDs were found in *LCAByg*. They were then constructed as materials in *LCAByg*, and generic C stages were added. The burnt wood included a C3 stage for wood materials (as mentioned in the EPD), and the phenolic foam's C4 stage was set to disposal, as mentioned in its' EPD. Construction wood, wood fiber insulation, aluminum profiles, and sheets were taken as generic EPDs from *LCAByg*. This introduced a limitation, as the EPD for burnt wood complied with EN 15804:2012+A2:2019, and GWP was thus declared separate (Okotomrerer, 2023). Thus, GWP-total was used for the A1-3 stages.

Fenestration systems challenged the LCI process. As described in section 3.3.3, finding separate properties for glazing and window frames was difficult, as acquiring EPDs with environmental impacts for specific window configurations and technical specifications directly from the manufacturer was impossible. To see if it would be possible to obtain the GWP for window frames, different glazing EPDs used in a window EPD were investigated in Figure 14.

Figure 14: Supporting rationale, EPD comparison and selection

Glazing EPD comparison

A comparison was made between two comparable EPDs from both glazing manufacturers and a generic glazing EPD (Rude, 3-lags energirude) (Aalborg University Copenhagen, 2024). The findings (Table 19) show an approximately 30 % difference between the two EPDs used for the *Velfac* EPD. The generic data set had a circa 8 % lower environmental impact than *PressGlass* and a 23 % higher impact than *Pilkington*. However, the generic EPD from *LCAByg* was only in accordance with EN 15804. These findings outline one of the issues with data certainty in the LCI phase.

Additionally, tools like the *OneClick LCA* library have hundreds of glazing types and window EPDs, including glazing and frames, which can have vastly different impacts. Separate frames, however, were not found. Separating glazing from frame EPDs is thus impossible without access to manufacturer tools.

Table 19: Glazing EPD comparison. References: ¹(PRESS GLASS Holding SA, 2023) ²(Pilkington, 2023b) ³(ÖKOBAUDAT, 2018)

	<i>PressGlass¹</i>	<i>Pilkington²</i>	<i>LCAbyg GenDK³</i>
Glass Type	IGU, triple	IGU, triple	Triple, energy pane
Construction	Triple glazing: 10 mm FG, 2 mm TSG, 2mm LSG, twice 16 mm spacer/cavity	4/12/4/12/4 Triple Igu With 2 X Offline Coated Glass	-
Functional Unit	1 m ² insulating glass	1 m ² insulating glass	1 m ² glass
Service Life	25 – 30 years	30 years	25 years
GWP (A1-3 and C2-4)	66.7 kgCO ₂ eq/m ²	48.6 kgCO ₂ eq/m ²	61.3 kgCO ₂ eq/m ²
System	GWP-total, EN 15804+A2 (CEN, 2019a)	GWP-total, EN 15804+A2 (CEN, 2019a)	GWP-total, EN 15804+A1 (CEN, 2013)

To find the environmental impact of the glazing, assemblies with the specifications provided by the manufacturers were built in Pilkington Spectrum, which provides GWP for assemblies based on Pilkington EPDs. System boundaries of Pilkington EPDs are cradle-to-grave with module D (Pilkington, 2023a). Even though module D is included in Pilkington EPDs, it was found empty in all checked ones. Pilkington Spectrum does not offer a detailed calculation, so it was not guaranteed that D was empty for all calculations. Pilkington EPDs also included A4 and A5 with generic values for Europe and B2, which were not excluded due to the tool limitations. All glazing assemblies were built in Pilkington Spectrum, so it was decided to accept this limitation. The environmental impacts of all glazing assemblies are shown in Table 20, which shows GWP impacts for the service life (30 years) and the whole life span of the building, where glazing will be replaced once.

Table 20: Environmental impact of glazing (Pilkington Spectrum, 2025). Detailed constructions are shown in Figure 39 through Figure 47.

Window		GWP, service life [kgCO₂eq/m²]	GWP, 50 y [kgCO₂eq/m²/y]
New Side	3-layers, LowE (<i>SKN154, solrude</i>)	9.60E+01	1.92E+00
	3-layers, Standard (<i>Standard rude</i>)	5.10E+01	1.02E+00
	2-layers, Double Glazing (<i>Edge</i>)	3.20E+01	6.40E-01
Sec. Side	1+2 layers, Double Glazing (<i>Edge</i>)	4.10E+01	8.20E-01
	1+2 layers, Double Glazing (<i>Bøjsø</i>)	4.80E+01	9.60E-01
	1+3 layers, Standard (<i>Standard rude</i>)	4.20E+01	8.40E-01
Top	2-layers, Clear (<i>T Clear Double</i>)	7.30E+01	1.46E+00
	2-layers, Solar (<i>T Sun Double</i>)	5.60E+01	1.12E+00
	3-layers, Clear (<i>T Clear Triple</i>)	8.40E+01	1.68E+00
	3-layers, Solar (<i>T Sun Triple</i>)	8.10E+01	1.62E+00

A test was performed where the found environmental impacts (Table 19) for the two glazing types were subtracted from the overall GWP for the Velfac window with a hybrid wood-aluminum frame to see the frame's impact. The Velfac window had a total impact of 81 kgCO₂eq/m². After subtracting values for the glazing, this would leave 14.4 kgCO₂eq/m² frame impact if the glazing was from PressGlass and 32.5 kgCO₂eq/m² if the glazing was by Pilkington. Generic hybrid wood-aluminum window frames from the LCAbyg database (Aalborg University Copenhagen, 2024) had an impact of 64.4 kgCO₂eq/m² for hybrid wood-aluminum frames.

Due to these complications and the discrepancies found, it was decided to utilize generic GWP impacts from LCAbyg for frames. Frame U-Values were taken from *EN ISO 10077* (CEN, 2017a). A limitation of the frames was that environmental impacts were per square meter window in the European standard window size (1.23 x 1.48 m) and were not adjusted for larger or smaller windows. An overview of the GWP of varying building parts is shown in Table 21, and a detailed overview of all building parts can be found in Table 38, Appendix A.

Table 21: Environmental impact of varied building parts. Impact in GWP, [kg CO₂eq / m² (construction) / y (50 years)]. Building parts marked with * are in GWP in kg CO₂ eq / floor / year. Sourced from LCAByg.

Building Part		Total	A1-3	B4	C3	C4
Envelope	New Roof Cassettes	5.67E-01	-5.78E-01	2.08E-02	1.11E+00	9.39E-03
	Existing Concrete Walls / Demo.	1.34E+00	1.29E+00	0.00E+00	2.69E-02	2.00E-02
	Phenolic Foam Wall	1.38E+01	1.38E+01	0.00E+00	0.00E+00	1.26E-03
	Wood Fiber Wall	5.96E-01	-1.29E+00	0.00E+00	1.88E+00	0.00E+00
	Aluminum Window frame	2.21E+00	2.00E+00	0.00E+00	1.38E-01	6.52E-02
	Plastic Window frame	1.76E+00	1.14E+00	0.00E+00	5.56E-01	6.52E-02
	Wood alu Window frame	1.29E+00	6.82E-01	0.00E+00	5.41E-01	6.52E-02
	Wooden window frame	7.12E-01	1.27E-01	0.00E+00	5.20E-01	6.52E-02
	Shading (blinds)	1.42E+00	4.69E-01	7.10E-01	2.41E-01	0.00E+00

Emission factors for building energy (Table 22) were taken from the Danish building regulations (BR18, 2018, Appendix 2, 8). These factors are based on projections for future emissions (Sørensen Nilsson et al., 2023). Emissions between the five-year adjustments were interpolated for years between data points using *GhPython* in Grasshopper. 2040 values were used for years between 2040 and 2050.

Table 22: Emission factors for electricity and district heating in GWP [kg CO₂ eq/kWh], future projections (BR18, 2018)

	2025	2030	2035	2040
Electricity	0.135	0.0470	0.0414	0.0403
District Heating	0.0878	0.0713	0.0688	0.0680

Future emission factors are projected to decrease, contrasting a recent Danish study that investigated the impact on biomass emissions, which is further explained in Figure 15.

Figure 15: Supporting rationale, biomass for district heating data selection

Influence of the environmental impact of biomass on WLC

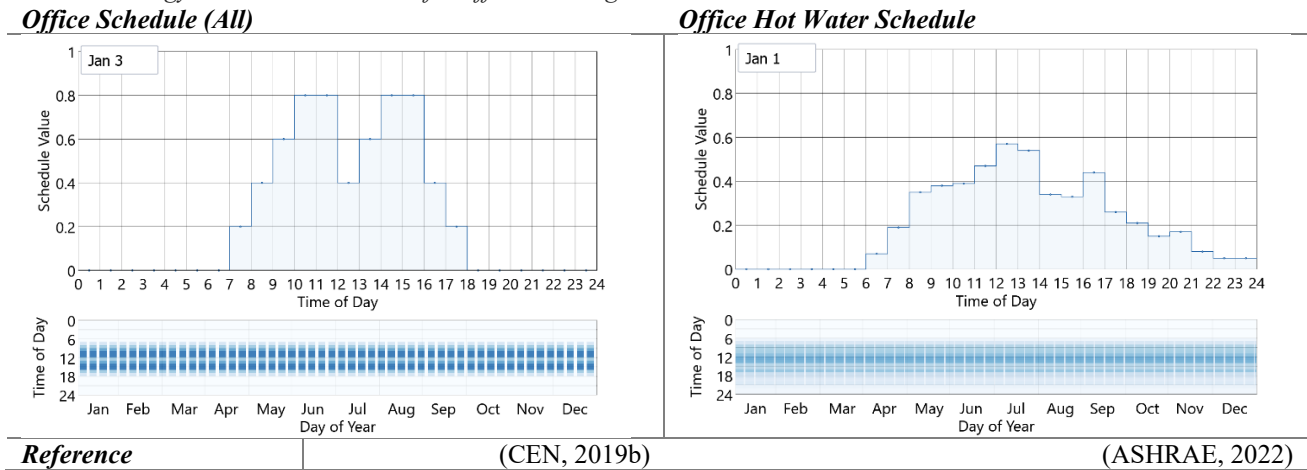
A recent study by Søgaard et al. (2024) investigated the effect of utilizing actual emission factors of biomass, like wood. Biomass is currently considered climate neutral, as its environmental impacts are accounted for under Land Use, Land-Use Change, and Forestry (LULUCF) in its country of origin only. In Denmark, 80 % of biomass is imported, and its impact is thus not considered when calculating emission factors. They found that emission factors for district heating would be ten times higher if direct emissions from burning biomass were included. Utilizing these values instead would thus double the buildings' total LCA. However, for this study, the emission values were taken from the building regulations (BR18, 2018).

3.4.2 Operational Energy Use Simulations

Dynamic energy simulations were run to calculate the operational energy use for the B6 stage. CS E+ interface was the simulation engine used to run the dynamic simulations (Solemma, 2024). CS was chosen because it had a low computation time (Rezaei Oghazi, Andersen, et al., 2024). The operational energy use for the building was calculated according to methods outlined in Danish building regulations and the Danish Building Research Institute's publication *SBI 213* (2018). The energy use for offices is calculated and weighted according to regulations, which must include "heating, ventilation, cooling, domestic hot water and lighting per m² of heated floor area may not exceed 41.0 kWh/m²" (BR18, 2018, § 250 - § 256).

Table 23 provides two schedules based on European standards. The office schedule is applied to all loads except for hot water. A different schedule was applied to deal with the specific conditions of hot water use in the office building because the schedule was not available in European standards.

Table 23: Energy simulation schedules for office buildings



In Table 24, two façade systems are shown, both with different thicknesses. To reduce computation time, it was investigated how much the fixed shading from the resulting overhang around the windows affected the final EUI result of the building. The result was a less than 1 % difference in all buildings. Based on this finding, fixed shading in the energy simulation was omitted.

Table 24: Percentual increase to total EUI with different fixed shading by building

Façade Types	Sawtooth Roof (SB)	Barrel Roof (BB)	Flat Roof (FB)
Phenolic foam + Alu.	0.08 %	0.08 %	0.05 %
Wood fiber + burnt wood	0.14 %	0.21 %	0.07 %

Thermal comfort was limited in this study because the scope was on the building level. Instead of performing a detailed assessment on the room level, the overheating hour threshold of ≤ 100 hours above $26\text{ }^{\circ}\text{C}$ was calculated for each zone in the energy model (BR18, 2018).

Table 25 contains values aligned with Danish energy standards for office buildings. When data was unavailable or restricted by a paywall, values were taken from the *Input and Output E+ Standards EnergyPlus* (2022). Unit conversions were performed for occupant density and envelope air infiltration from ACH 50 Pa to ACH 4 Pa, as these conversions were necessary for CS E+ input compatibility. Assumptions were made for various values. The energy source type was chosen based on the Copenhagen region. Shading was controlled by a setpoint rather than a schedule, with CS E+ default values used to simplify calculations. The shading type was assumed to be external for side lighting to avoid additional thermal comfort studies. Top lighting had interior blinds due to the limited availability of external shading solutions for low-angle top lighting, for example, in the FB formal typology.

Table 25: Overview of energy simulation input parameters

Parameters	Value	Reference
Occupancy	People density (P/m ²)	0.057 (SBI 213, 2018)
	Metabolic rate (met)	1.2 (SBI 213, 2018)
	Occupancy schedule (h)	1560 (SBI 213, 2018)
	Max air speed (m/s)	0.2 (EnergyPlus, 2022)
Equipment	Equipment power density (W/ m ²)	6 (SBI 213, 2018)
	Equipment availability schedule (h)	1560 (SBI 213, 2018)
Lighting	Lighting power density (W/ m ²)	10 (SBI 213, 2018)
	Lights available schedule (h)	1560 (SBI 213, 2018)
	Target Lux	300 (SBI 213, 2018)
	Dimming type	Continuous (SBI 213, 2018)
Hot Water	Heating COP (unitless)	1 (EnergyPlus, 2022)
	Inlet temperature (°C)	10 (SBI 213, 2018)
	Water supply temperature (°C)	55 (SBI 213, 2018)
	Flow rate per person (m ³ /h/P)	0.0005 (SBI 213, 2018)
	Hot water energy source	District Assumption

Heating	Heating set point (°C)	21	(SBI 213, 2018)
	Heating COP (unitless)	1	(SBI 213, 2018)
	Heating schedule (h)	8760	(EnergyPlus, 2022)
	Heating energy source	District	Assumption
	Heating sizing factor (unitless)	1.25	(EnergyPlus, 2022)
	Maximum supply temperature (°C)	35	(EnergyPlus, 2022)
Cooling	Cooling set point (°C)	24	(SBI 213, 2018)
	Cooling COP (unitless)	3.6	(SBI 213, 2018)
	Cooling schedule (h)	8760	(EnergyPlus, 2022)
	Cooling energy source	Electric	Assumption
	Cooling sizing factor (unitless)	1.25	(EnergyPlus, 2022)
	Maximum supply temperature (°C)	12	(SBI 213, 2018)
Mech. Vent.	Min Fresh Air Person (L/s/P)	7	(SBI 213, 2018)
	Min Fresh Air Area (L/s/m ²)	0.35	(SBI 213, 2018)
	Mechanical ventilation schedule (h)	8760	(EnergyPlus, 2022)
	Heat recovery efficiency (%)	0.85	(SBI 213, 2018)
Envelope	Envelope constructions	See Section 3.3.1	
	Infiltration ACH (ACH at 4 pa)	0.06	(SBI 213, 2018)
	Infiltration constant coefficient	1	(SBI 213, 2018)
Windows	Window glazing constructions	See Sections 3.3.2 and 3.3.4	
	Shading system type (Side Lighting)	Exterior shade	Assumption
	Shading system type (Top Lighting)	Interior shade	Assumption
	Shading control type (unitless)	On if high solar on window	(EnergyPlus, 2022)
	Shading availability schedule (h)	8760	(EnergyPlus, 2022)
	Shading system set point (W/ m ²)	150	(EnergyPlus, 2022)
	Shading system transmittance (%)	0.22	CS Library
	Frame conductance (W/ m ² K)	Varied	(CEN, 2017a, 2017a)
	Frame width (m)	Varied	(CEN, 2017a, 2017a)
	Natural ventilation	AllOff	(SBI 213, 2018)

3.4.3 Daylight Simulations

The Rhino and Grasshopper plug-in, Climate Studio (Solemna, 2024), was used for simulations. The software was chosen due to the low computation time (Rezaei Oghazi, Andersen, et al., 2024), comprehensive material libraries, and grasshopper integration. The plug-in also included a pre-set workflow that was created according to requirements set by the European daylight standard.

3.4.3.1 Material Properties

The European Daylight Standard provides recommended reflectance values for opaque materials. These values are listed between a base and high range: “ceiling 0,7 to 0,9; interior walls 0,5 to 0,8; floor 0,2 to 0,4; exterior walls 0,2 to 0,4; with exterior ground usually set to 0,2” (CEN, 2021a). Table 26 represents the chosen input material reflectances within the ranges stated in the daylight standard. A series of tests were conducted to find suitable material reflectances, as shown in Figure 16.

Table 26: Chosen opaque material reflectance

	Floors	Ceilings	Walls	Frames	Terrain
Rvis (%) Sim.	40 (High Range)	90 (High Range)	50 (Base Range)	70 (Base Range)	20 (Base Range)

A couple of pass or fail tests were performed to test reflectances sensitivity before inputting settings into the daylight simulation. The study did not vary opaque material reflectance during optimization because a review of EPDs indicated that many manufacturers do not provide specific information on the environmental impact of different paint finishes, necessitating further investigation beyond the study's focus. This Supplementary information is described as a note in Figure 16.

Figure 16: Supporting rationale, material reflectance selection

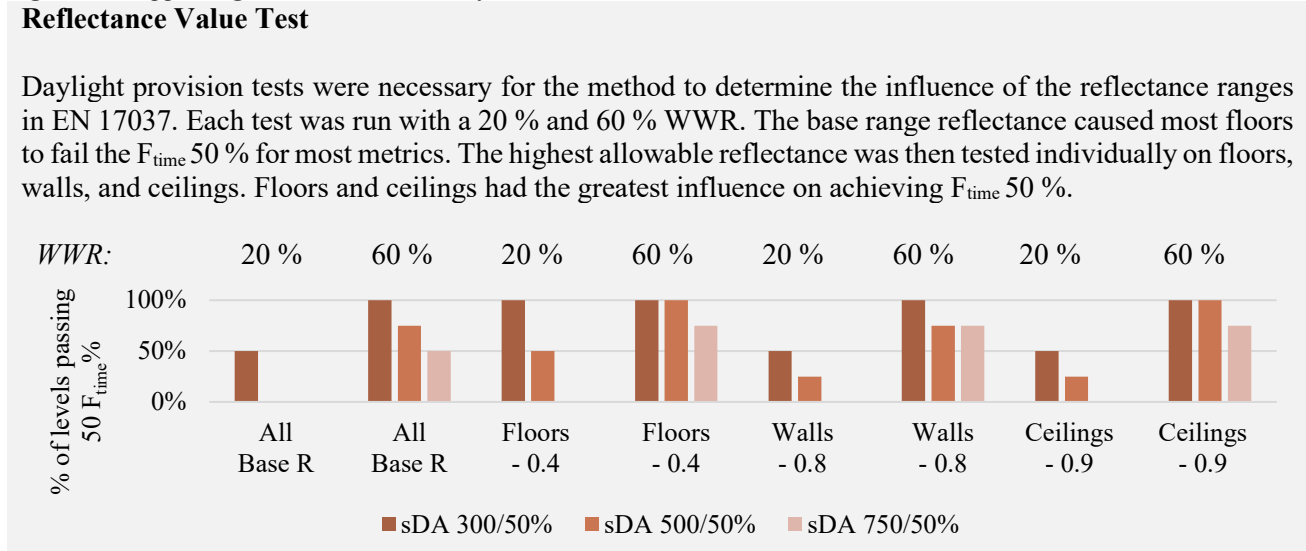


Table 27 and Table 28 outline the glazing properties used in the daylight model. Custom BDSF files could not be generated for each glazing construction, which is needed to achieve a complete alignment between glazing radiance materials and data sourced from the *Pilkington Spectrum* program (Pilkington, 2024). A column is added to describe the percentual difference between the simulated and actual T_{vis} from the product data sheets. The percentual difference was between 1 % to 4 %.

Table 27: Side lighting glazing material properties

Side Lighting Glazing	T_{vis} (%) Sim.	T_{vis} (%) Actual	% Difference
3-layers, LowE (SKN154, solrude)	51	47	4
3-layers, Standard (Standard rude)	73	74	1
2-layers, Double Glazing (Edge)	84	82	2
1+2 layers, Double Glazing (Edge)	76	76	0
1+2 layers, Double Glazing (Bøjsø)	69	71	3
1+3 layers, Standard (Standard rude)	70	68	2

Table 28: Top lighting glazing material properties

Top Lighting Glazing	T_{vis} (%) Sim.	T_{vis} (%) Actual	% Difference
2-layers, Clear (T Clear Double)	80	80	0
2-layers, Solar (T Sun Double)	51	51	0
3-layers, Clear (T Clear Triple)	72	72	0
3-layers, Solar (T Sun Triple)	45	46	1

Window shading properties were aligned with the CS Energy Plus simulations. The model for shading activation in the daylight model could not be in complete alignment with the energy model due to the different simulation engines. Instead, the shading activation was set according to *LM-83-12 Approved Method: Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)* IES (2012).

3.4.3.2 Simulation Settings

The grid settings in Table 29 are calculated according to the daylight standard calculation rules in Appendix B.2 (CEN, 2021a), and all other radiance settings were kept at default according to CS.

Table 29: Daylight simulation settings according to CEN 169 (2021a)

Settings	Values
Grid Height (m)	0.85
Grid Wall Offset (m)	0.50
Grid Size (m)	1.75
Ambient Bounces (#)	10
Acceleration Devices	Nvidia GeForce RTX 3060 and Nvidia GeForce RTX 2060

Section § 379 of the BR18 (2018) requires good daylight performance in workspaces, dining rooms, and kitchens. For this study, the definition from the Danish regulations was utilized and streamlined with other Danish data in the study, such as LCA. It was found that definitions for daylight grid differ between certifications and standards (Figure 17).

Figure 17: Method Supplementary note, daylight grid definition overview

Differences in the Definition of Regularly Occupied Spaces

EN 17037 loosely defines the daylight grid as: “all spaces that may be regularly occupied by people for extended periods except where daylighting is contrary to the nature and role of the actual work done” (CEN, 2021a). Depending on the regulations or certification system that daylight is assessed for, the definition of “regularly occupied” changes: LEED defines them as spaces where people spend more than one hour per person per day, which could include meeting/conference rooms and offices (LEED, 2024). BREEAM only requires 30 minutes of daily occupancy per building user, including canteens and break spaces (BREEAM USA, 2020). In contrast, the Danish Building Regulations (BR18, 2018) do not define spaces based on occupants' time but on the spaces' function.

A UDI analysis was performed for each floor plate surrounding the atria to establish a daylight grid for occupied spaces. Initially, a 10 m area from the facade was analyzed, but sDA analyses revealed that even with the highest WWR and reflectances, it was not possible to comply with all metrics. This can also be explained by Lechner & Andrasik (2022, p. 415), who outlined that the first 4.5 m from the façade can be considered fully daylit, and an additional 4.5 m can be expected to be partially daylit, thus not reaching the highest performances.

It was necessary to achieve all the performance levels investigated; therefore, the grid was reduced to a 6 m area from the facades. A 6 m grid around the facades led to varying areas for regularly and irregularly occupied spaces per FT due to varying perimeters, which meant that the BB typology would have the largest regularly occupied area, whereas the SB typology would have the smallest (Table 30).

Table 30: Regularly and irregularly occupied areas per formal typology

	<i>Sawtooth Roof (SB)</i>	<i>Barrel Roof (BB)</i>	<i>Flat Roof (FB)</i>
Total Reg. Occ. Area	2882 m ²	4733 m ²	3742 m ²
Total Irreg. Occ. Area	6644 m ²	4373 m ²	5503 m ²

This 6 m grid was also found to comply with regulations regarding view, even though view out was not considered in this study. The minimum horizontal view angle is recommended to be 14 ° (CEN, 2021a). Thus, an adequate distance from windows for which good view quality can be guaranteed can be calculated based on window width: At a minimum WWR of 20 %, windows in our study were 1.3 m wide, leading to circa 5.5 m with an adequate view, which corresponds to three desks placed side by side as the work plane area (Figure 18).

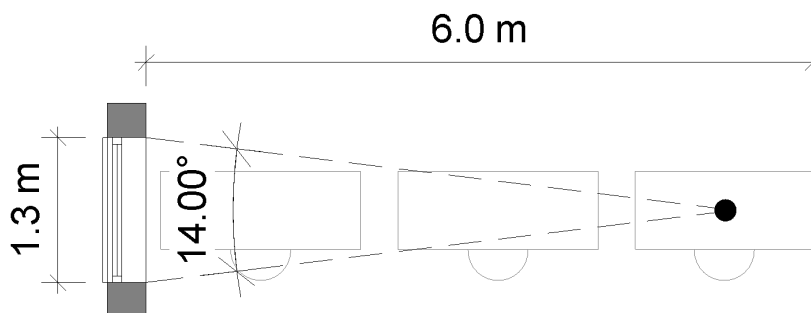


Figure 18: Principal sketch to determine grid size and compliance with view out

3.4.4 Multi-Objective Optimization Simulations

Most problems are not solved by only changing one objective function but by finding a compromise between multiple (Chong & Zak, 2011). Multi-objective optimization (MOO) can help find this compromise. When MOO results are plotted in a scatter plot, Pareto optimal solutions can be defined as a group of points that pose equally advantageous solutions (Chankong & Haimes, 1983).

A master thesis by Baden and Taghizadeh (2023) found Opossum to be the best MOO tool regarding time efficiency and success rates for both hypervolume, so the proximity of found solutions to the Pareto optimal front and minimum values. Based on this, it was decided to utilize Opossum in this study. Opossum has different single- and multi-objective optimization algorithms (Wortmann, 2017). In this study, just as in the reference study (Baden & Taghizadeh, 2023), the Radil Base Function Method (RBFMOpt) algorithm was employed. This algorithm constructs a surrogate model of the design space and thereby decreases computation time by estimating the global optimum (Costa & Nannicini, 2018).

To determine the number of combinations needed for optimization, Baden and Taghizadeh's (2023) study was reviewed. They found that when 30 consecutive runs showed no improvements, resulting in the optimizer stopping, the MOO had a 100 % chance of finding the optimal solution. However, it was decided to reduce the simulation time to 20 runs without improvements, which was still found to have a 99.7 % success rate in the reference study. According to Baden and Taghizadeh (2023) and Rezaei Oghazi (2024), this process should find the optimal solution after running circa 10 % of all possible combinations.

The study used two objectives: minimizing LCA and maximizing sDA at the building level (Table 31). The unit for WLC was provided by § 297 - § 298 of the BR18 (2018), and minimization was chosen to reach LCA limit values. Based on preliminary simulation validation tests, the most challenging level to achieve is the threshold level of 500 E_{TM} lx. Even though this was found, the study maximized each daylight provision level (minimum, medium, and high) (CEN, 2021a) individually at the building level to prevent the optimization from focusing on parameters that only fit the highest threshold. The Opossum optimization was run three times (optimizing for each E_{TM} lx metric) for each formal typology, amounting to a total of nine optimizations. The elapsed time was about 4 days on two computers.

Table 31: Objectives overview and unit

Objectives	Objective Units (Optimized at Building Level)
Minimize Whole Life Carbon (LCA Total) for each formal typology (FT)	kg CO ₂ -equivalents per m ² per year. Based on HFA over 50 years. Per FT
Maximize Daylight provision (E_{TM} lx metrics) for each formal typology (FT)	sDA average for (100 E _{TM} lx, 300 E _{TM} lx, and 500 E _{TM} lx). Per FT

3.5 Data Handling and Visualization

Data was exported from GH to Excel using the *TT Toolbox*. Additionally, the data from Opossum was saved. These results computed the total hypervolume of each parameter combination, indicating the volume of space dominated by a point in a scatter plot and the quality of the Pareto front (Bringmann & Friedrich, 2013).

The fixed base values per FT were added to the overall GWP in Excel. The results of the MOO were then filtered to include results that fulfilled the following performance criteria: LCA ≤ 7.5 kgCO₂eq./m²/y, EUI ≤ 41 kWh/m²/y, overheating hours ≤ 100 hours above 26 °C, and the optimized threshold of sDA 100 E_{TM} lx, 300 E_{TM} lx, and 500 E_{TM} lx for ≥ 50 F_{time},% as well as 300 E_T lx, 500 E_T lx and 750 E_T lx for ≥ 50 F_{time},%. Scatter plots were made manually in Excel. The same filtering approach was used to create box plots for each FT. Scatter plots were subsequently visually inspected.

Some graphs were created in MATLAB to investigate parameter combinations and their performance. To write the scripts, YouTube tutorials, help forums, and generative AI (ChatGPT and Gemini) aided the development. AI helped find fitting statistical methods and develop the code. An iterative approach was then used to debug and troubleshoot the script with generative AI and help forums.

MATLAB was used to investigate parameter distribution in scatter plots. For this, tutorials and steps from the Matlabs website and questions in the MATLAB community were used in the first place. Afterward, debugging was done with the help of Gemini. The script (Figure 49) loads data from an Excel sheet with the filtered simulation results. Then, the E_{TM} results for the y-axis and the parameter that points should be colored by are set, followed by chart size and custom colors for the points in the plot. Then, it extracts the data for the chosen settings and rounds numeric values into two decimal spots to simplify computation. It then finds unique values in the chosen parameter column and saves the values and colors. As a debugging step, an error was integrated in case there were more categories than colors. The figure is then plotted, and its look can be customized.

A scoring script for MATLAB was developed to post-process simulation results and investigate successful parameter combinations. The first step in scoring parameter combination (Figure 50) was normalization to make LCA and sDA comparable due to their different scales and weighable in a sensitivity analysis. To do this, results were scaled between 0 and 1. For LCA (Eq. 3), lower values were scaled to one, whereas for sDA (Eq. 4), higher values were scaled to one.

$$s_i = 1 - \frac{(x_i - x_{min})}{(x_{max} - x_{min})} \quad (3)$$

$$s_i = \frac{(x_i - x_{min})}{(x_{max} - x_{min})} \quad (4)$$

LCA results were minimized (Eq. 3), where s_i is the normalized score. The lowest LCA result in the column would thus have a normalized score of $s_i = 1$ when $x_i = x_{min}$. The highest LCA result is $s_i = 0$ when $x_i = x_{max}$. Other scores are scaled within the range. sDA results were maximized (Eq. 4). Here, the lowest sDA result in the column would have a normalized score of $s_i = 0$, and the highest result, $s_i = 1$, due to the same principle as Eq. 3. Furthermore, x_i is the value (result) in each scale, x_{min} is the column's lowest value, and x_{max} is the highest value in the column. The combined scores for sDA and LCA are then saved in an added column in a normalized matrix, where a higher score indicates larger sDA and lower LCA results.

The data was then investigated further. Subsequently, the results were weighted, with 100 % LCA and 0 % each daylight provision threshold result, leading to 100/0 weighting for environmental and daylight performance, which was later changed and investigated in a sensitivity analysis. Afterward, all normalized results were multiplied by their weight to create a composite score for the parameter combination. As a last step, values were filtered by their optimization objective for daylight performance (low, medium, or high). Conducting a sensitivity analysis was later deemed unnecessary as reaching above compliance sDA results of 50 % for each metric does not contribute to reaching higher thresholds.

After the scoring procedure, data was visualized as parallel plots using a script in MATLAB (Figure 51). First, due to pre-simulation runs before MOO, duplicates were manually removed in the top five design combinations in Excel. The top five were then plotted as parallel plots and filtered by level if needed. Input for the code was taken from MATLAB (2025), and debugging was done using Gemini.

4 Results

The results are organized into seven sections (Figure 19). Section by section, the results zoom in, concluding with the top combination for each formal typology according to the current and future CO₂ limit values.

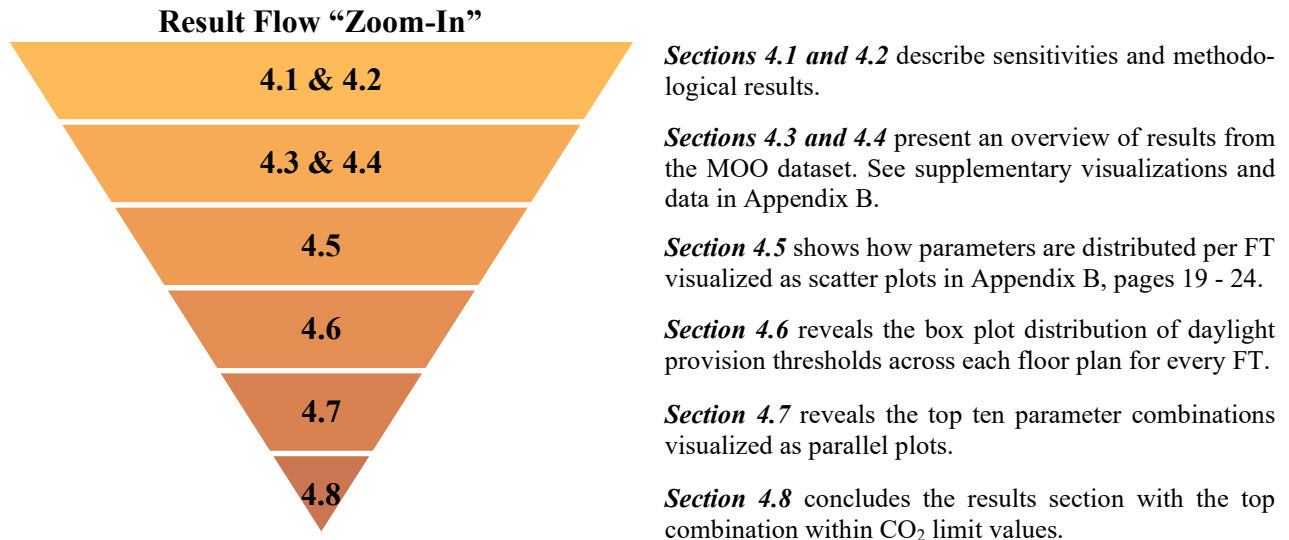


Figure 19: Overview of how the results (Section 4) are organized.

4.1 Sensitivity Analysis

A sensitivity analysis was performed to see the impact of data certainty for the fixed building elements for every FT, as shown in Figure 19. Here, SB, BB, and FB refer to the FT. *MEAN* indicates that only mean reference values were used, and *LOW* indicates that only low ones were used. *LCAbyg MEAN/LOW* means that specific values from LCAbyg were utilized, and impacts for installations were either mean or low HFA-based reference values.

Regardless of whether reference values from HFA or more detailed material-based generic values were used, the sawtooth roof had the highest environmental impact. There was a 27 % reduction in impact between the mean and low reference values. When more specific values were used, the impact for fixed elements was reduced by 55 % for LCAbyg values and mean reference values and 60 % for LCAbyg and low reference values.

The higher impact on some FTs was primarily due to the demolition of existing top lighting. The demolition outweighed the benefits of a reduced area of interior glazed walls (Figure 19). The FB consistently showed the lowest impact across all scenarios. This was due to its smaller interior glazed area, as the roof shape did not increase wall height, and to the limited area of existing top lighting, resulting in lower demolition impacts. Additionally, decks showed a lower environmental impact when specific data for wooden decks was used instead of generic data. This was largely due to the exclusion of a new terrain deck and the fact that the reference value was based on buildings with a high proportion of concrete decks.

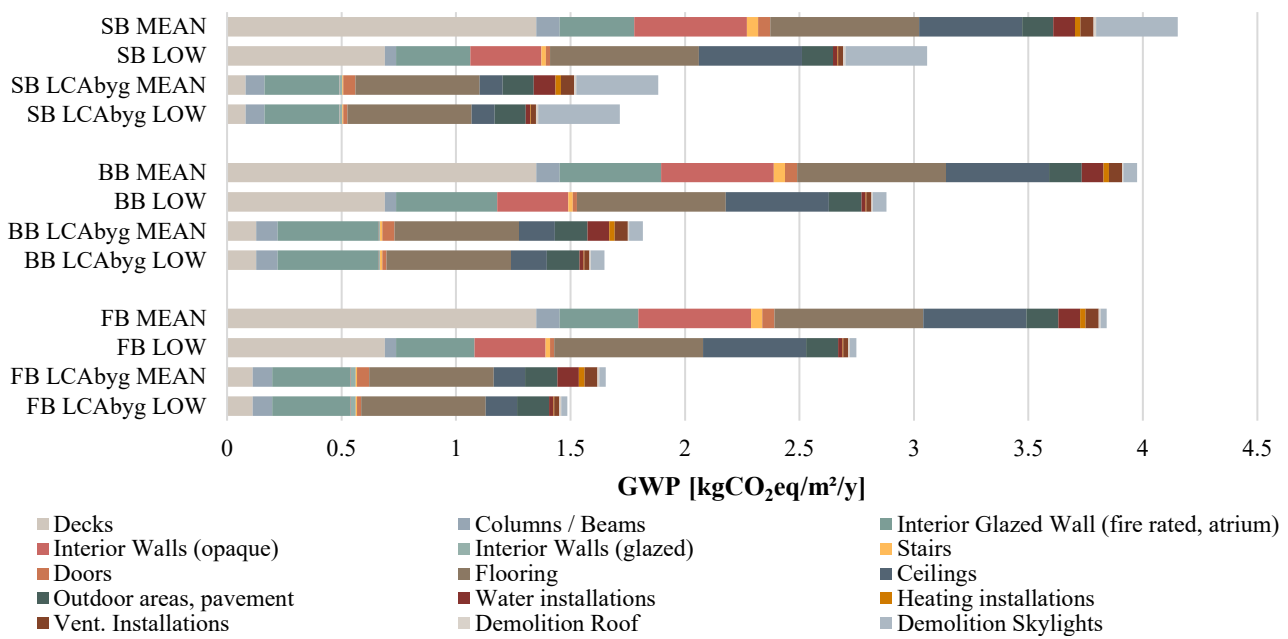


Figure 20: Sensitivity analysis data certainty LCA

The percentage impact of each building part on the total WLC for each FT reveals differences between all FTs (Figure 20). The flooring was the largest contributor to WLC in all FTs, followed by fire-rated glass walls around the atrium, ceilings, and outdoor areas. Skylight demolition impact greatly varied between FTs due to varying WRR, making it the second contributor to WLC. Interestingly, the relative total impact of decks was about the same in the FB and BB, even though the BB had an extra floor.

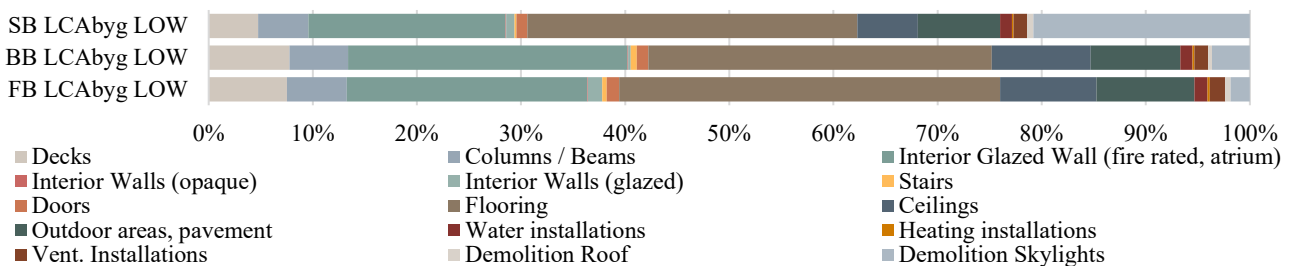


Figure 21: Percentual GWP impact of fixed building elements for each FT

Figure 20 highlights that HFA-based reference values led to GWP results equaling 40 % - 60 % of the allowed carbon budget for the LCA limit value of 7.5 kgCO₂eq/m²/y. It was thus deemed impossible to reach those limits, as the envelope and operational impacts were not yet included. LCAbyg and low reference values were thus used to calculate the WLC of all FTs.

4.2 Life Cycle Inventory Challenges

Whole life cycle carbon calculations were subject to scope and data limitations that have influenced the results. The selected materials did not have uniform system boundaries. The assessment of glazing extended through more life cycle stages (production to end of life) than the assessments of other materials. This inconsistency is a limitation and makes a direct comparison between materials on an equal basis difficult. For instance, the additional LCS (A4 - 5, B2, D) included in Pilkington EPDs accounted for approximately 13 % of the overall GWP. By contrast, the generic EPDs from LCAbyg included a 10 % GWP contingency. If this was also true in GWP calculated in Pilkington Spectrum, impacts might be more comparable than initially thought.

However, the uncertainties around the included LCS persist. Additional challenges arose when sourcing EPDs for glazing assemblies. Window EPDs were based on glass assembly EPDs from several manufacturers, and separate EPDs were not provided for the frame. This could have allowed subtracting frame impact to see only the glazing impact. A comparison between two triple-glazing EPDs from varying manufacturers used for Vefac EPDs revealed a 30 % impact difference. Increasing the environmental impact of glazing by 30 % would significantly impact a building’s WLC, stressing the limitation data uncertainty poses for aligning environmental and daylight performance.

4.3 Multi-Objective Optimization Overview

The MOO simulations returned different numbers of simulations per formal typology and simulated $E_{TM\ lx}$ threshold (Table 32). Out of the possible 3 456 unique parameter combinations, the minimum requirement MOO generally stopped after the lowest number of simulations. For the SB, the medium stopped after the largest percentage of simulations, whereas the BB ran the lowest number of simulations for the medium. In the FB, medium and high both stopped after 7.2 %.

This meant that fewer parameter combinations were simulated than the expected 10 % with the chosen simulation settings and algorithm. This is a potential limitation, as it could mean that the combination yielding the lowest GWP while still achieving compliant sDA was not found. This outcome could potentially have been caused by the stochastic nature of daylight simulation results, which were used for the sDA calculation (Nazari & Matusiak, 2024).

Table 32: Number of Simulations runs until 20 iterations without improvements were reached and percentage of the total

Total	Minimum	% of All	Medium	% of All	High	% of All
SB	127	3.7 %	256	7.4 %	224	6.5 %
BB	223	6.5 %	169	4.9 %	247	7.2 %
FB	159	4.6 %	212	7.2 %	248	7.2 %

Figure 21 shows points optimized for sDA performance for a specific illuminance on 95 % of the floor area for a minimum of 50 % of all daylight hours. The FB (circles) achieves the lowest GWP results among the three typologies, followed by the BB (triangles) and SB (crosses) buildings. All simulated solutions comply with the current BR18 LCA limit but only approximately 70 % with BR25, indicated by a vertical dashed line. Whereas GWP stayed within 5 to 11.5 kgCO₂eq/m²/y, sDA ranged from 0 % to 95 %. The area marked in grey contains solutions with phenolic foam insulation instead of mineral wool. When looking at sDA performance in illuminance per 50 % area per 50 % of the time, LCA results remain fairly similar to 95 %, but sDA ranges between 10 % and 90 %.

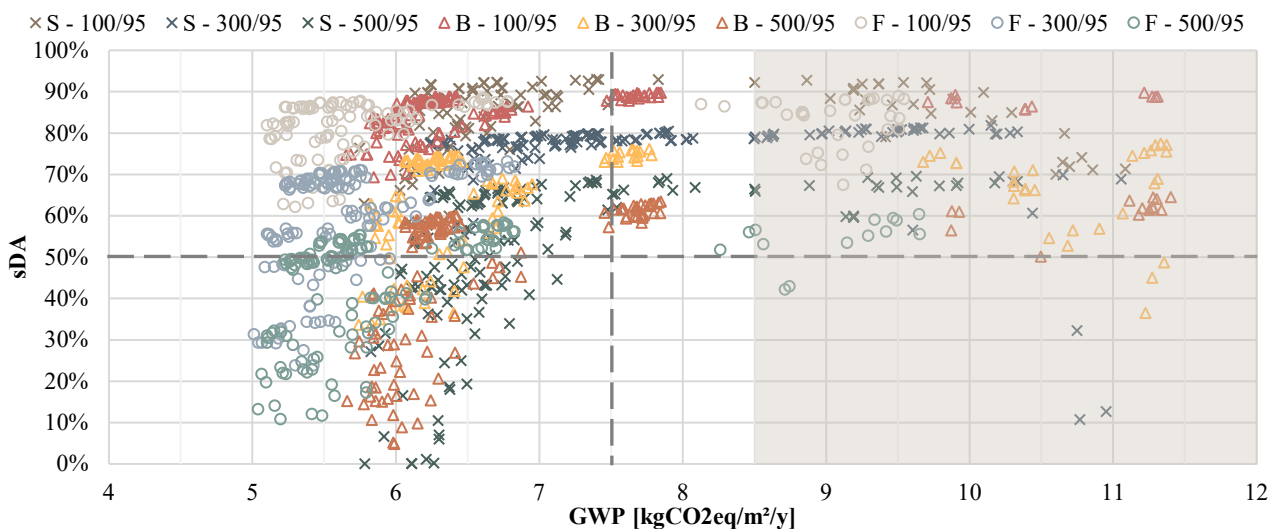


Figure 22: Scatter Plot sDA (x/95%) and LCA

4.4 Daylight and Environmental Performance Trends

Figure 22 shows zero-ranked parameter combinations found by Opossum when optimizing LCA and sDA for 95 % of the area. A rank of zero means that these combinations have a large hypervolume and, thus, dominance over a large area. Other solutions do not dominate these points on the Pareto front. Most points lie above the 50 % sDA threshold; however, some points are included that achieve sDA values of sub-50 % but the lowest GWP values per simulation.

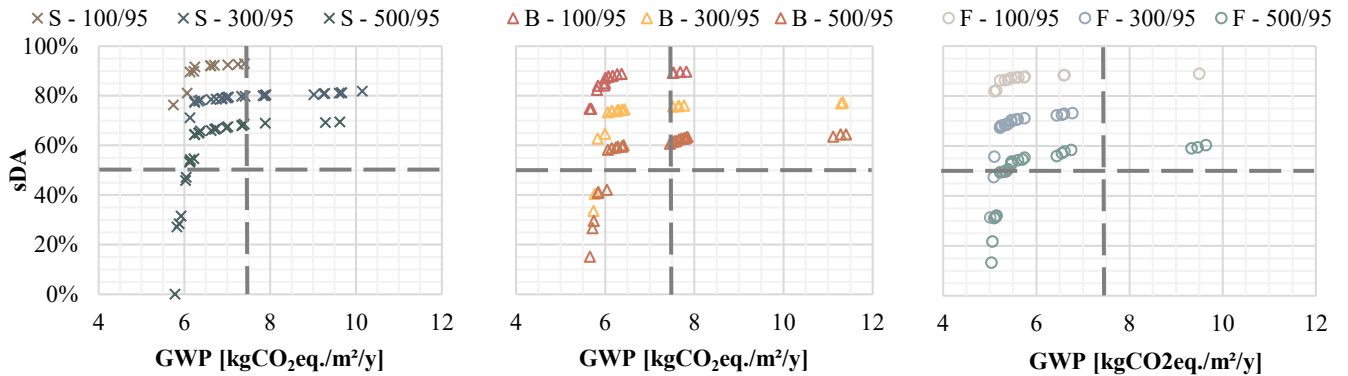


Figure 23: Pareto front based on Opossum results by FT. The horizontal dashed line indicates the 50 % threshold for sDA, and the vertical dashed line shows the 7.5 kgCO₂eq./m²/y LCA limit, taking effect in July 2025 (BR25).

Furthermore, Figure 22 seems to show a trend, resembling a logarithmic curve, between sDA and GWP. This means that as sDA increases, GWP also increases, but the increase rate slows down after a certain point for each simulation. This suggests that achieving higher sDA values using the tested parameters became progressively more challenging. Specifically, this point occurs approximately at 90 % sDA for minimum, 70 % sDA for medium, and 60 % sDA for maximum optimization results in all FTs. This point corresponds to GWP values of around 6 kgCO₂eq/m²/y for the SB, 5.7 kgCO₂eq/m²/y for the BB, and 5 kgCO₂eq/m²/y for the FB.

All simulation results were subsequently investigated: SB is shown in Figure 23 and Figure 24, and Appendix B has graphs for BB (Figure 53 and Figure 54) as well as in FB (Figure 55 and Figure 56). These figures plot all points within the thresholds for sDA and limit values for GWP, overheating hours, and EUI. The graphs include trendlines that highlight visually observed patterns. However, these do not imply any statistically significant correlation.

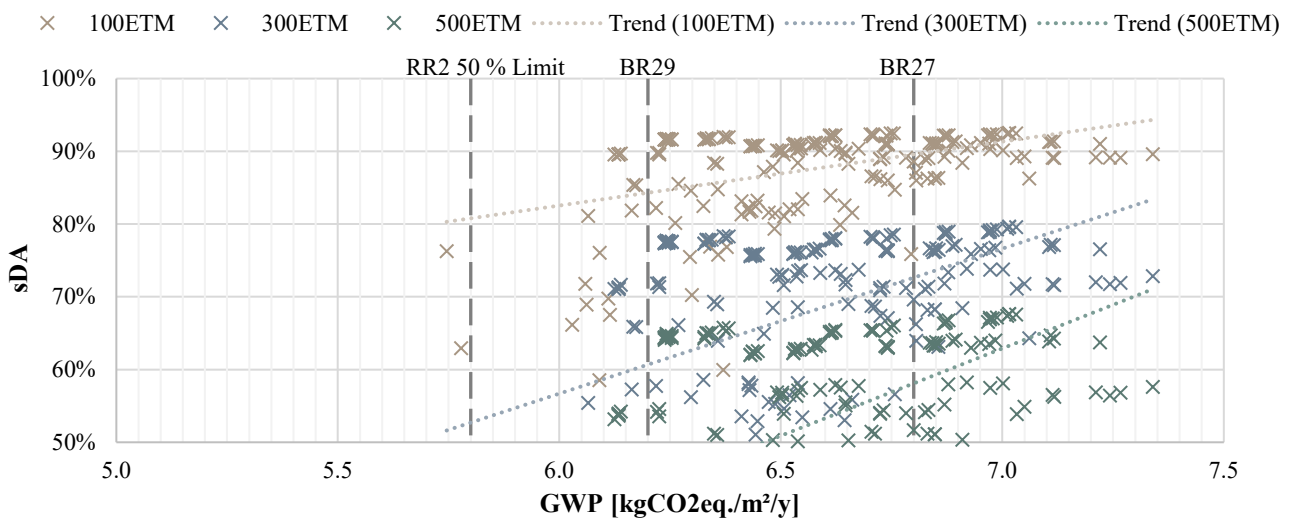


Figure 24: Sawtooth Typology (SB) scatter plot, LCA and sDA (E_{TM})

For the SB, the dotted trendlines in Figure 23 show a slight positive trend between sDA and GWP, similar to that observed in the other FTs. Points optimized for the lowest daylight performance reach the lowest GWP values and show the steepest increase in GWP when increasing sDA. Notably, points filtered for overheating mostly had open blinds for over 90 % of the time.

Figure 24 suggests a similar slight positive trend between sDA and GWP using low-carbon insulation, but trendlines were more gradual compared to E_{TM}. This slight positive trend was consistent across all FTs. The slope for the minimum MOO results in BB and FB typologies varied.

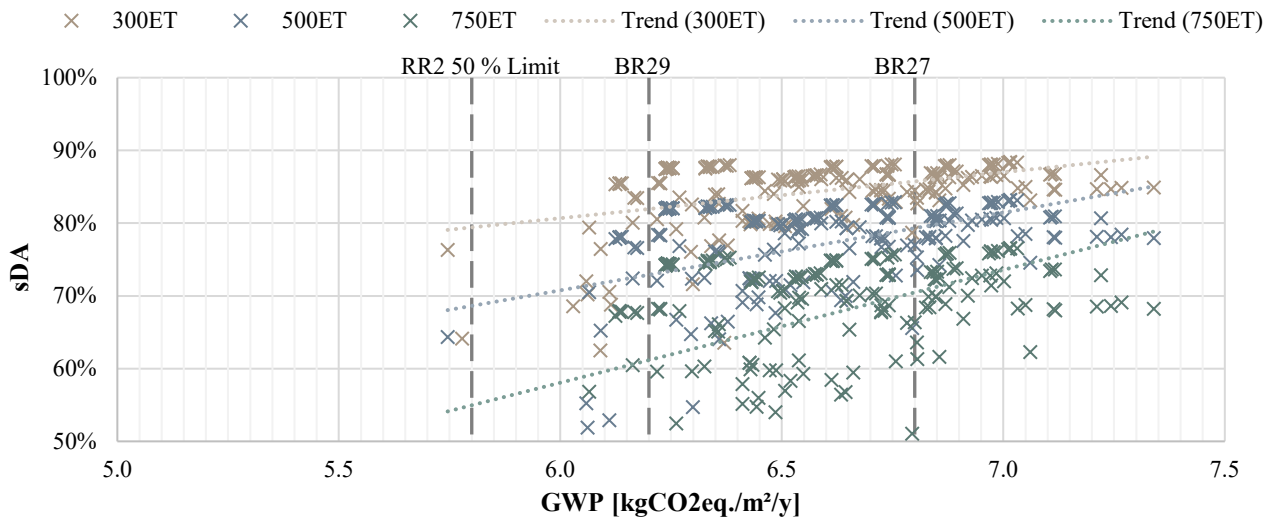


Figure 25: Sawtooth Typology (SB) scatter plot, LCA, and sDA (E_T)

Table 33 to Table 35 show the number of simulated values that fall within the limit values for each future revision to limit values. Only less than 60 % of minimum and less than 30 % of medium and high optimization simulations for the SB comply with limit values for LCA (2025 limits), EUI, overheating hours, and sDA thresholds. Looking at future limits (Table 33), out of all minimum simulations, 49 % could comply with the 2027 limit values, 12 % with limits for 2029, and only 1.6 % with suggested RR2 limits. For both medium and high, only approximately 40 % comply with 2027 limits, whereas 2029 and RR2 have compliance of around 1 %.

Table 33: Percentage of total MOO simulations compliance with limit values SB formal typology

SB FT	BR25	% of Total	BR27	% of Total	BR29	% of Total	RR2 50% likelihood	% of Total
Minimum	73	57.5 %	62	48.8 %	15	11.8 %	2	1.6 %
Medium	69	27.0 %	40	15.6 %	1	0.4 %	0	0.0 %
High	54	24.1 %	42	18.8 %	3	1.3 %	0	0.0 %

BB results did not show a negative trend as steeply between lowered GWP limits and compliance as the SB. It showed similar compliance percentages as the SB for BR25 minimum and high limits, though higher compliance for medium. Higher daylight performance thresholds showed a larger percentage of compliant results than in the SB for BR27 and BR19. RR2 limits were not reachable.

Table 34: Percentage of total MOO simulations compliance with limit values BB formal typology

BB FT	BR25	% of Total	BR27	% of Total	BR29	% of Total	RR2 50% likelihood	% of Total
Minimum	117	52.5 %	71	31.8 %	65	29.1 %	3	1.3 %
Medium	69	40.8 %	64	37.9 %	30	17.8 %	1	0.6 %
High	58	23.5 %	57	23.1 %	18	7.3 %	0	0.0 %

The FB showed the lowest compliance for high threshold results but was similar to the other FTs for minimum daylight threshold compliance with BR25 limits. It also showed no compliance differences between BR25 and BR29 and complied with potential RR2 thresholds.

Table 35: Percentage of total MOO simulations compliance with limit values FB formal typology

FB FT	BR25	% of Total	BR27	% of Total	BR29	% of Total	RR2 50% likelihood	% of Total
Minimum	80	50.3 %	80	50.3 %	80	50.3 %	71	44.7 %
Medium	76	35.8 %	76	35.8 %	75	35.4 %	63	29.7 %
High	19	7.7 %	19	7.7 %	19	7.7 %	18	7.3 %

Even though it was established that the solutions with phenolic foam insulation did not comply with LCA limit values, it is interesting to note that their scatter plot suggested a negative trend, meaning that an increase in sDA led to lower LCA results (Figure 25) until a tipping point at around 9.1 kgCO₂eq/m²/y, after which no clear trend can be observed, however, the trend seems rather positive. The sDA increase was primarily caused by increasing the glazed areas for side and top lighting.

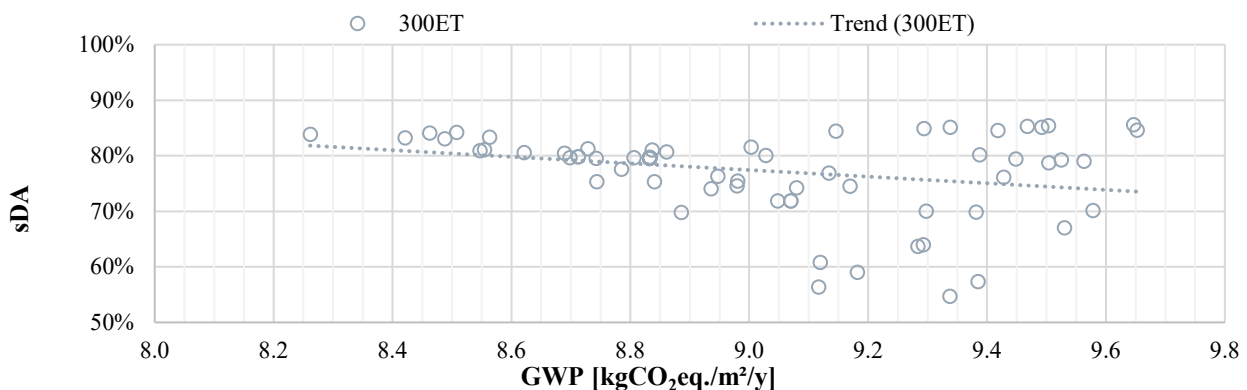


Figure 26: sDA and LCA correlation for solutions with phenolic foam. Shown here, for minimum optimizations in FB FT

4.5 Parameter Distribution per FT

An investigation was made into the MOO parameter distribution using scatter plots, which are shown in Appendix B. The results revealed that all daylight provision thresholds could be reached in all FTs, and there was a visible clustered distribution of design parameter combinations.

The distributions for the SB formal typology (Table 42) illustrate that the base glazing area and a fully glazed atrium reached the lowest LCA results, followed by the base geometry, and both combined had the highest whole-life-carbon result but did not substantially increase sDA. WWR was less clustered in the scatter plot, but generally, higher WWR contributed to higher sDA and LCA. For minimum thresholds, 30 % WWR reached the lowest LCA while maintaining an above 75 % sDA. For medium and high, 40 % and 60 % WWR were better. Side lighting glazing showed no obvious ideal solutions, but most points along the Pareto front used standard triple glazing. Double glazing alternatives increased the sDA slightly in some points, but only while increasing LCA by a more significant percentage. The frames did not show clear trends, except for aluminum, which contributes to lower sDA and higher LCA results. As side and secondary glazing, triple glazing seemed advantageous when wanting to decrease LCA. If slightly higher LCA results are permissible, double glazing increased sDA very slightly. Clear glass was beneficial for top glazing, as double glazing did not yield significantly higher sDA results than triple glazing. LowE glazing performed worse for both objectives.

The distributions for the BB formal typology (Table 43) reveal that the top design alternatives had a less clustered distribution of points, but all design options could reach each daylight threshold. For top lighting, there was a clear positive correlation between glazing amount and LCA and sDA, with base geometry achieving the lowest results. In contrast, a combination of base top lighting and a fully glazed

atrium had the highest results for both objectives, and the same finding was found regarding the glazing amount applied to WWR. All WWR percentages complied with minimum thresholds, 30 % - 60 % with medium and only 60 % with high levels. For side light glazing, clear triple glazing performed better for sDA and LCA results compared to LowE glazing. Double glazing was only chosen in one parameter combination and did not perform better than other combinations. Regarding window frames, PVC was chosen in combination with the lowest LCA values and wood for the highest sDA. The other frame options performed worse. Triple glazing was the optimal secondary glazing solution. Double glazing (Bøjsø) was the second-best performing glazing with a slightly higher T_{vis} and U -value of 1.2 W/m²K but the highest GWP among the three options. Clear triple glazing yielded the highest sDA values and lowest LCA for top glazing, followed by LowE triple glazing.

The distributions for the FB formal typology (Table 44) showed that the base geometry (scattered skylights) resulted in the lowest LCA results for top lighting. Slightly higher sDA results were attainable when atria were glazed in combination with the base geometry. When only glazing the atria was the sDA lower than the base geometry. However, all designs were able to fulfill all threshold levels. WWR showed that 40 % reached the lowest LCA result, whereas 60 % had the highest sDA. High daylight thresholds were only achievable with 60 % WWR. As for the other buildings, triple glazing reached the best results for side lighting, and frames were less clearly distributed. Wood seemed to be included in many of the best-performing parameter combinations. For secondary glazing, triple glazing perform best, though all glass types were included in combinations that reached all thresholds. The same finding applied to top glazing, where clear triple glazing performed slightly better than the other types.

4.6 Daylight Provision Thresholds er FT

The box plot graphs visualize the filtered MOO data and represent the daylight performance on each floor, separated by the three FTs and the maximized metric 500 E_{TM} for $\geq 50 F_{time, \%}$. The MOO maximization thresholds 100 E_{TM} lx and 300 E_{TM} lx for $\geq 50 F_{time, \%}$ are in Appendix B, Figure 57 to Figure 59. Each box plot describes the distribution of sDA values expressed as the fraction of daylight hours during which the target illuminance (E_T) and minimum target illuminance (E_{TM}) are met for each floor. The box plots are organized by level and the daylight standard minimum, medium, and high targets. A red horizontal boundary line represents $\geq 50 F_{time, \%}$ and indicates daylight hour compliance. Values below this line represent a failure to meet the daylight criteria in the standard.

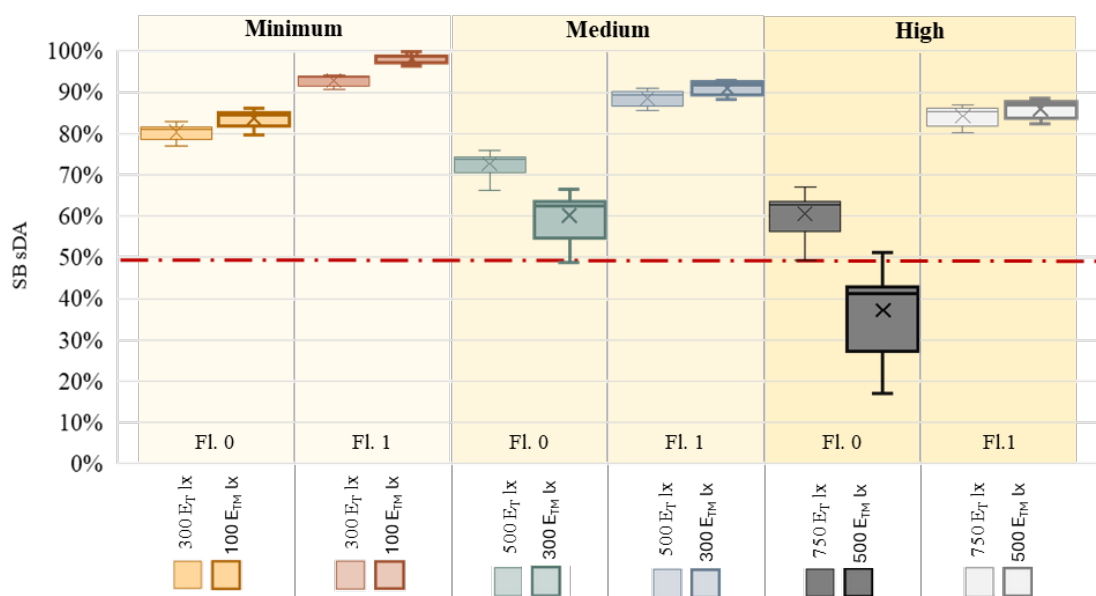


Figure 27: Box plots of SB formal typology represented by floor and threshold

In the SB typology (Figure 26), all data lies above the 50 % line for minimum and medium thresholds. However, there was a notable decline in performance on Floor 0 for the high threshold, where only few maximum values complied.

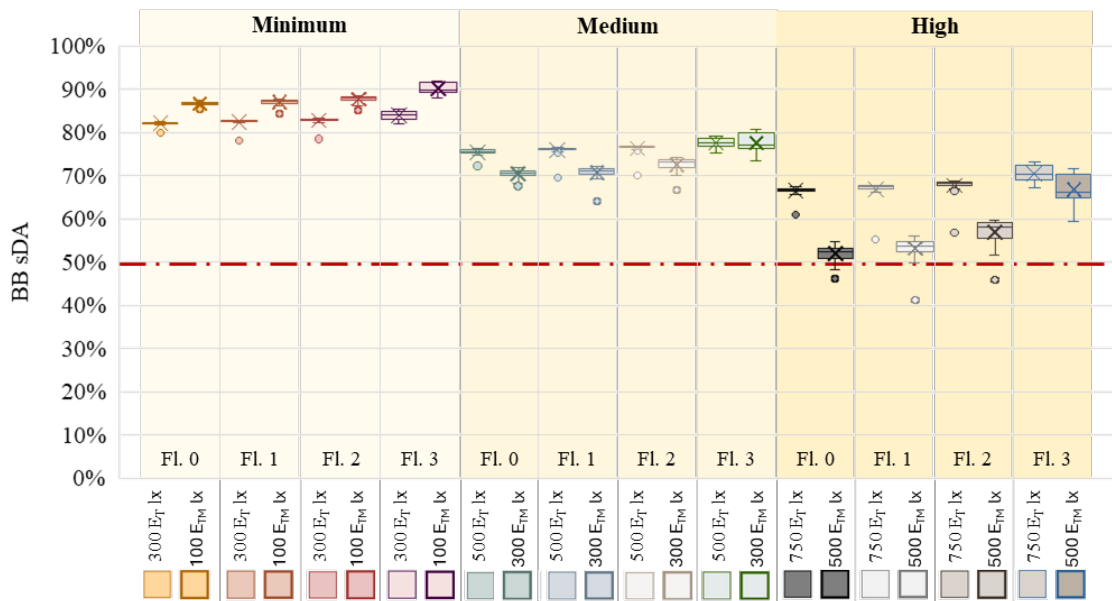


Figure 28: Box plots of BB formal typology represented by floor and threshold

The BB typology (Figure 27) demonstrates consistent daylight performance, with the median, interquartile range, and upper whiskers of most floor distributions exceeding 50 F_{time} , % across each floor. Only for high performance did a few outliers and lower whiskers for the ground floor do not comply.

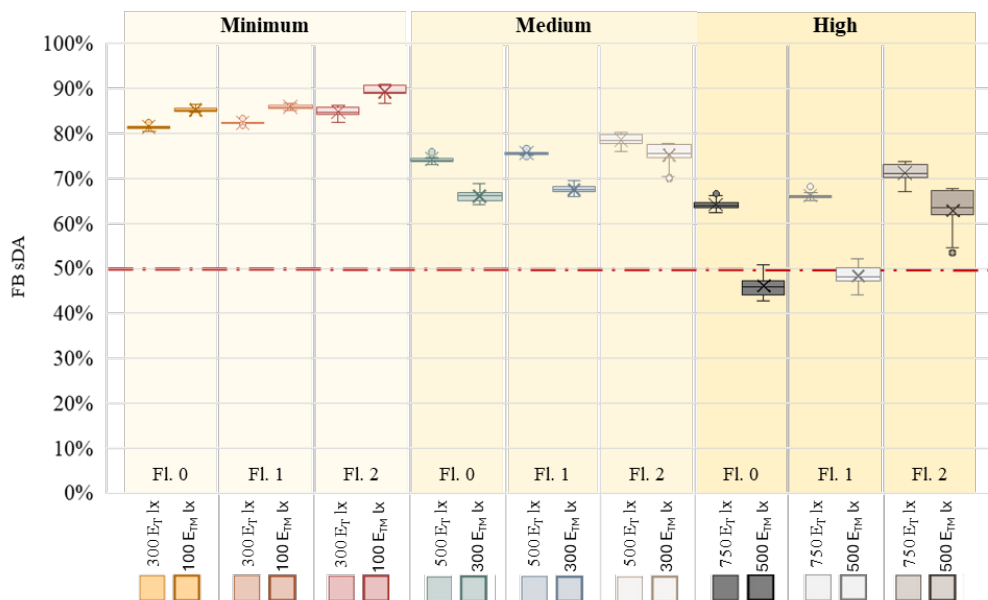


Figure 29: Box plots of FB formal typology represented by floor and threshold

The FB typology (Figure 28) had similar distributions to SB and BB for minimum and medium, where all floors were above 50 F_{time} , %. However, for the high threshold, distributions were below the boundary line for floors 0 to 1.

A typical pattern was seen in all figures and the appendix across all FTs. This pattern occurs in all minimum thresholds where the distributions reveal $E_T \text{ lx} < E_{TM} \text{ lx}$. A switch occurs for medium and high, and $E_{TM} \text{ lx} < E_T \text{ lx}$.

4.7 Top Ten Parameter Combinations per FT

To identify the top ten parameter combinations for the SB, BB, and FB, the optimized datasets were filtered, normalized, and weighted based on LCA and sDA. The parameter combinations were visualized using parallel coordinate plots. These plots display the configuration of input parameters across multiple axes and allow for comparison of the top-performing solutions under minimum, medium, and high daylight provision thresholds. Each line in the plot represents the set of parameter combinations that output environmental and daylight performance results. Appendix B provides detailed information with data tables.

In the SB (Figure 29), the top lighting for the minimum threshold was a fully glazed atrium, while the base geometry was preferred for both medium and high thresholds. Three of the five selected configurations used a WWR of 20 % for the minimum threshold, and two used 30 %. In the medium threshold, three of the five configurations used a WWR of 60 %, and two used 40 %. In the high threshold, four of five used 40 %, and one used 60 %. Side lighting primarily used standard glazing in the medium and high thresholds, with less use in the minimum threshold. For existing windows, secondary standard triple glazing (SecStd) with a T_{vis} of 74 % and a U -value and g -value of approximately 0.52 was selected in all five cases for medium and high thresholds and in three of five cases for the minimum. Window frame selection varied across the optimization results. For the minimum threshold, two configurations used PVC frames, two used aluminum, and one used a hybrid frame. For the medium threshold, three used PVC, one used a hybrid, and one used a wood frame. The high threshold had two configurations using PVC frames, one using aluminum and two using a hybrid frame. The ideal top glazing was clear triple glazing (TCTrp), which was chosen for medium and high, and minimum had two of five solutions with LowE coated triple glazing.

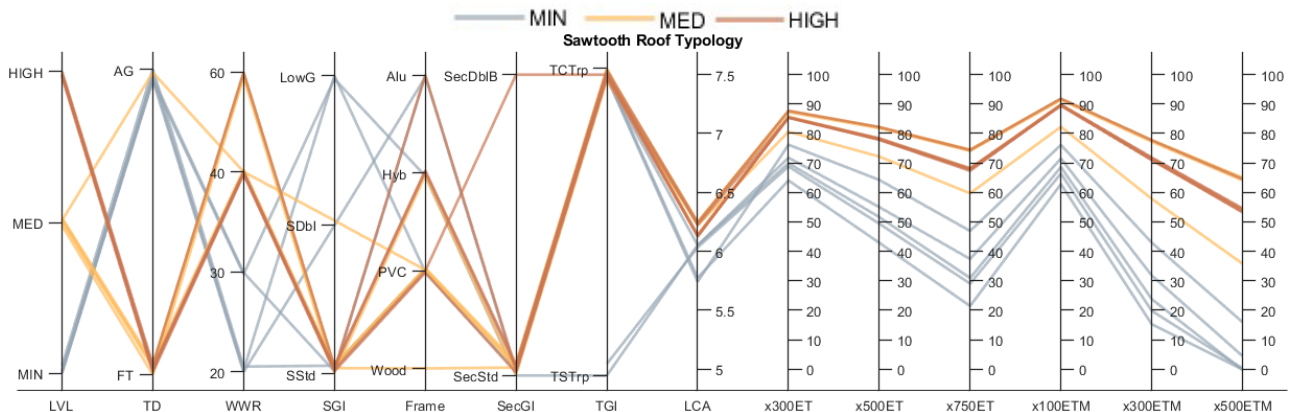


Figure 30: Parallel plot of top five parameter combinations for the sawtooth roof (SB) formal typologies. WWR, x300ET, x500ET, x750ET, x100ETM, x300ETM and x500ETM are in percentage [%].

In the BB (Figure 30), the base geometry was the primary top lighting across all thresholds. The base geometry and glazed atrium were combined once at minimum threshold. A fully glazed atrium was selected twice in medium and four out of five times at high. The WWR increased across thresholds: 20 % for minimum, 40 % for medium, and 60 % for high. A WWR of 30 % appeared once in both minimum and medium thresholds. SStd was used for side lighting across all thresholds. For existing windows, SecStd was selected in most cases. The secondary double glazing (SecDbl), with the highest g -value, U -value, and T_{vis} configuration, was selected twice in the minimum threshold. The other double glazing option (SecDblB), with a slightly lower g -value, U -value, and T_{vis} , was chosen once for the medium threshold. Window frame selection varied. For the minimum threshold, four configurations used PVC frames, and one used a wood frame. At the medium threshold, one used PVC, one used aluminum, and three used wood. At the high threshold, one used PVC, three used hybrid frames, and one used wood. The most frequently selected top glazing type was TCTrp. LowE-coated

triple glazing (TSTrp) was selected twice in both the medium and high thresholds. Clear double glazing (TCDbl) appeared once in medium, and LowE double glazing (TSDbl) once in high.

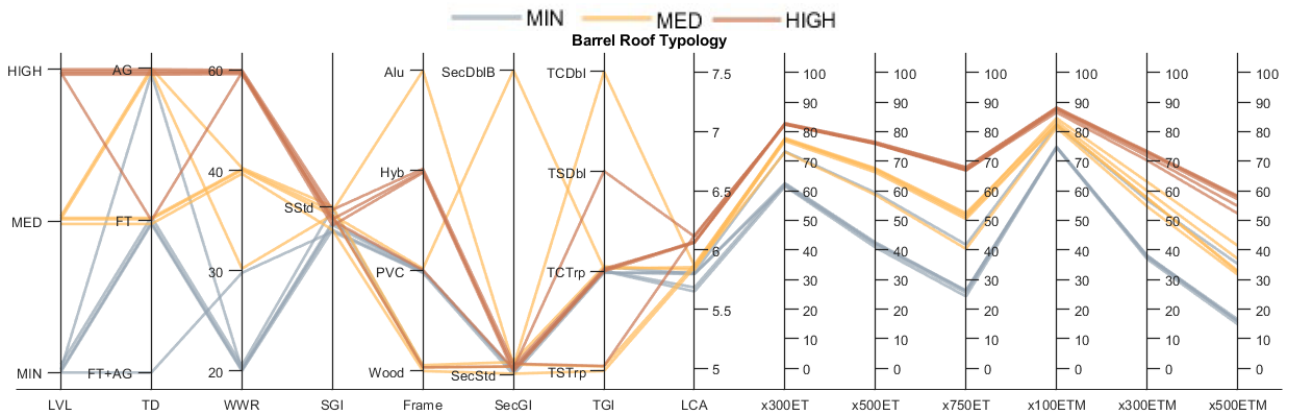


Figure 31: Parallel plot of top five parameter combinations for the barrel roof (BB) formal typologies. WWR, x300ET, x500ET, x750ET, x100ETM, x300ETM and x500ETM are in percentage [%].

In the FB (Figure 31), the base geometry was selected as the primary top lighting at the minimum and medium thresholds and once at the high threshold. A combination of the base geometry and glazed atrium was selected three times in the high threshold, while only glazing the atrium was selected once. The WWR increased with the threshold level: 30 % at minimum, 40 % at medium, and 60 % at high. A WWR of 40 % was also selected twice in the minimum threshold. SStd was used for side lighting across all thresholds, and it was also selected as secondary glazing for existing windows in most configurations. SecDbl was selected once in the high threshold, while SecDblB appeared once at both the minimum and medium thresholds. Window frame selection varied. At the minimum threshold, two configurations used PVC frames, and one instance of each aluminum, hybrid, and wood frame was observed. At the medium threshold, two used PVC, aluminum, hybrid, and wood were each selected once. At the high threshold, one configuration used PVC, aluminum, or hybrid frames, and wood frames were selected twice. Top glazing was more varied in the FB. At minimum, TCTrp and TSDbl were each used twice, and TCDbl was used once. At the medium threshold, TCTrp appeared in three of five cases, while TCDbl and TSTrp were each used once.

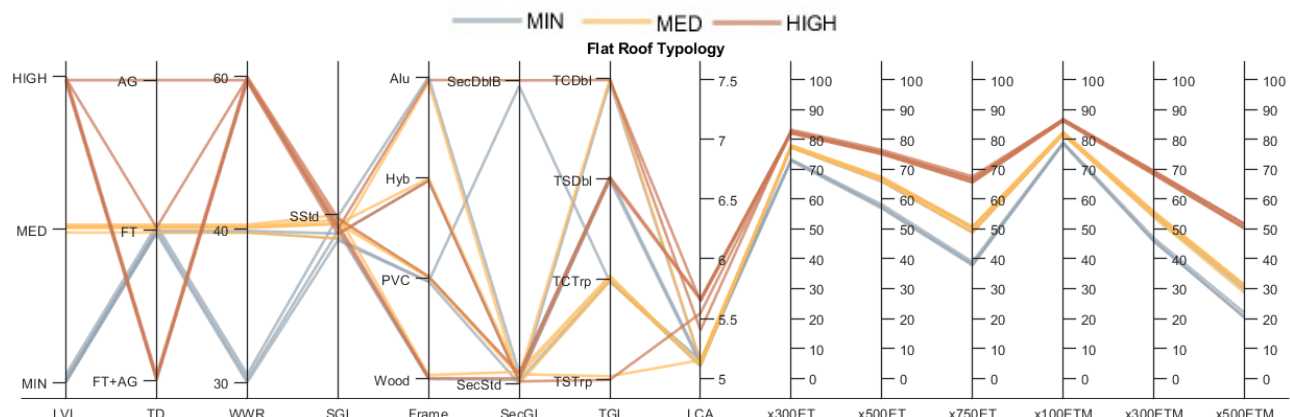









Figure 32: Parallel Plot of top five parameter combinations for the flat roof (FB) formal typologies. WWR, x300ET, x500ET, x750ET, x100ETM, x300ETM and x500ETM are in percentage [%].

4.8 Parameter Combinations within CO₂ Limit Range per FT

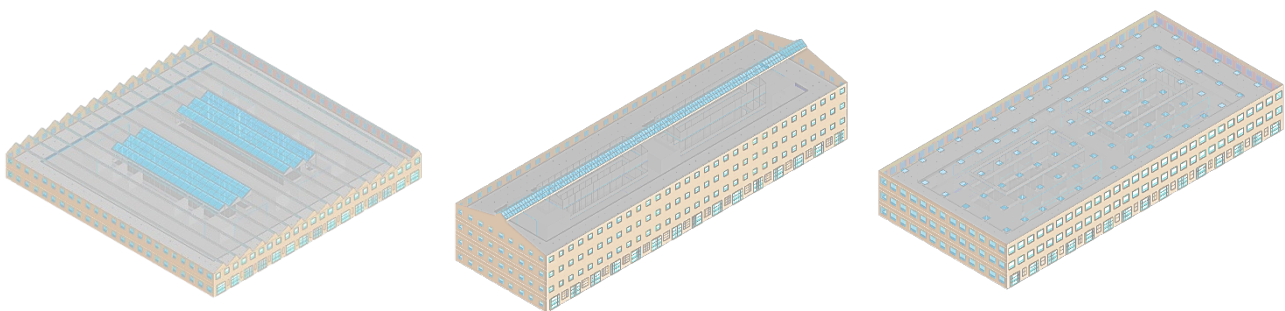
Table 36 below presents the top-performing combinations for each FT. Additional solutions can be found in Appendix B, Table 45, Table 46, and Table 47. The results again reveal a trend where increasing daylight provision through higher WWR and WRR corresponds to an increase in WLC, as

seen in the WLC column. The MOO identified that the optimal glazing type for both side and secondary side lighting is triple standard rube glazing (Section 3.3.3). For top lighting, the optimal solution was clear triple glazing (Section 3.3.5). When looking at window frames, no clear solution was found. While all values remain below the BR18 regulatory limit, only the FB typology meets the future BR25 limit and scope.

Table 36: Top combination overview of each formal typology

Daylight Provision Per FT								WLC kgCO ₂ eq./m ² /y	
	Envelope	WWR	WRR	Side Glazing	Secondary Glazing	Top Glazing	Window Frame	BR18	BR25
Minimum									
SB	Wood Fiber	30 %	34 %	Triple (Standard rube)	Triple (Standard rube)	(T.Clear Triple)	Alu	5.746	7.246
BB		20 %	14 %				PVC	5.652	7.152
FB		40 %	5 %				Hybrid	5.103	6.603
Medium									
SB	Wood Fiber	40 %	45 %	Triple (Standard rube)	Triple (Standard rube)	(T.Clear Triple)	PVC	6.133	7.633
BB		40 %	19 %				Wood	5.823	7.323
FB		40 %	5 %				Wood	5.102	6.602
High									
SB	Wood Fiber	60 %	45 %	Triple (Standard rube)	Triple (Standard rube)	(T.Clear Triple)	Hybrid	6.238	7.738
BB		60 %	19 %				Wood	6.062	7.562
FB		60 %	5 %				(T.Clear Double)	Wood	5.400

When WLC was weighed 100 % and when compliant with daylight provision, only minimum daylight provision can be met. The solutions are shown in Figure 32 and Figure 33. In the SB, the top solution utilized a fully glazed atria for top lighting, 30 % WWR, and aluminum frames. The BB solution features the base top lighting design, 20 % WWR, and PVC frames. The top design for the FB featured base design top lighting, 40 % WWR, and wood frames. All FTs' top combinations utilized standard, clear triple-glazing for side, secondary, and top glazing.



SB Top Solution

BB Top Solution

FB Top Solution

Figure 33: SB, BB, and FB top solution

In the SB, medium and high results were circa 7 % higher than the minimum, with the high threshold solutions being 0.2 % lower than the medium. In the BB, medium was approximately 3 % higher, whereas high was 4 % higher than minimum. In the FB, the medium solution's WLC result was the same as the minimum, and the high result was 6 % higher than the minimum.

The operational carbon of the SB was 5 % lower than that of the FB and 18 % lower than the BB. The main difference in operational carbon between the three FTs was heating energy demand. A complete overview can be found in Appendix B (Table 45 to Table 47).

If future impacts for the construction phase were to be added with the maximum allowable impact of 1.5 kgCO₂eq/m²/y.

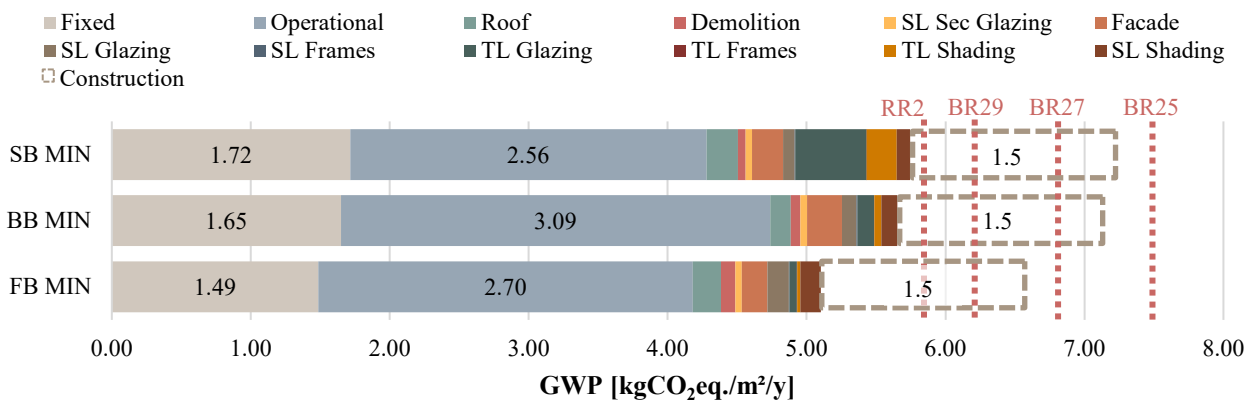


Figure 34: LCA for the top solution by FT

When these results are normalized and seen as percentages of the total environmental impact (Figure 34), the operative carbon is the largest contributor to WLC. The fixed parameter impacts add up to being the second largest contributor in all FTs. Due to the typologies' different form factors, the impacts of façade and roof differ. However, total opaque envelope impacts reach similar impacts, around 8 % for the SB and FB, with the BB being slightly lower at 7 %. As defined by demolition for openings, secondary glazing, new glazing, new frames, and shades, side lighting accounts for 6 % in the SB and the BB and 8 % in the FB. Top lighting, including frames, glazing, and shades, amounts to 9 % in the SB, 3 % in the BB, and 2 % in the FB. Side lighting added 6 % to the SB and BB and 8 % each to the FB. Fenestration, in total, thus accounted for 16 % of the SB and around 9 % of the BB and FB (Table 48, Appendix B).

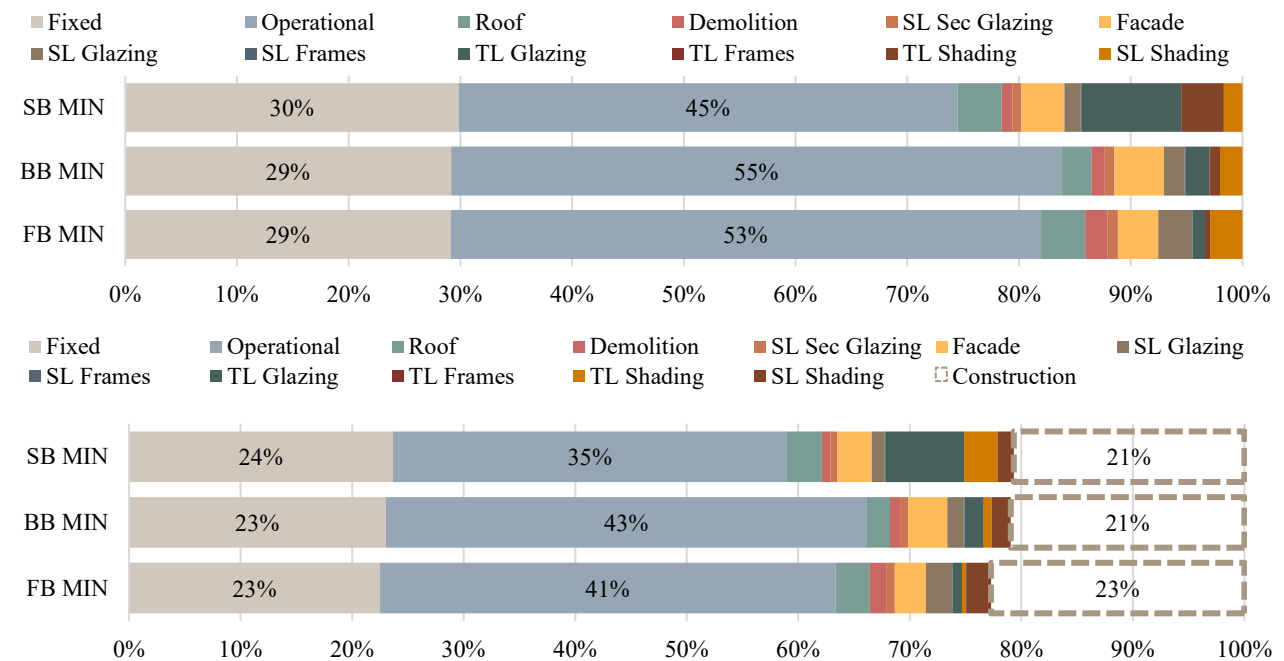


Figure 35: Normalized LCA for the top solution by FT. Without construction phase impact (top) and with construction phase impact (bottom).

5 Discussion

5.1 Aligning Environmental and Daylight Performance

The results indicate that aligning environmental and daylight performance when transforming industrial buildings into perimeter office spaces presents various interconnected challenges that must be overcome. The study found that achieving balanced performance in both areas is complicated by rapidly changing environmental regulations, outdated standards, and inconsistencies in EPDs, where declared values often differ from actual product performance.

Across Nordic countries, LCA was also deemed a challenge due to evolving and varying boundary conditions. On a national level, regulatory frameworks complicate alignment efforts, as daylight performance is typically assessed at the room level, while LCA is evaluated at the building level (BR18, 2018). This misalignment introduces difficulties in ensuring design decisions support environmental and daylight performance targets. Furthermore, daylight compliance is assessed early in the design phase, often during the permit application stage, while LCA verification usually occurs after construction. This increases the risk that design changes introduced later in the process compromise the original daylighting strategy.

In addition to regulatory and practical misalignments, some of the standards used to evaluate building performance are outdated or inconsistent. As discussed in the literature review, the TC 350 framework for sustainability has undergone multiple updates, such as the EN 15804 for EPDs. However, EN 15978 is outdated and should be aligned with these new updates to the sustainability framework. These discrepancies hinder comparability between assessments unless consistent standardization is applied. This fragmentation in national practices and standard revisions restricts comparability and may lead to misguided design strategies, complicating the alignment of building performance objectives.

Many figures and supporting tables found that a higher daylight provision seemed to increase GWP due to larger glazing areas and higher energy demand. This trade-off seemed greater in the E_T lx thresholds than E_{TM} lx, but GWP increased in both as daylight levels improved. Only low-carbon insulation and façade cladding remained below the BR25 LCA limit value. Carbon-intensive insulation had the opposite effect and exceeded the limit value in all cases. Increasing sDA decreased GWP, which was consistent with the literature. The results also showed that operational and daylight improvements from wall depth shading do not offset the embodied carbon of phenolic foam compared to wood fiber when both insulations have the same U -value.

The slight increasing trend between sDA and GWP observed in the low-carbon façade scenarios indicates that improvements in daylight provision generally lead to increased GWP. A statistical approach would provide better insights into the strengths of these trends.

The various transformation design choices also introduced impacts on embodied carbon, especially from fenestration systems. The extensive glazing, top lighting, and motorized blinds contributed significantly to the WLC of the FTs. Reaching the high daylight provision threshold was often only possible with a WWR of 60 %, while the glazed area was most influential for daylight provision and WLC. Varying glazing revealed that clear triple glazing was the most beneficial. LowE triple glazing did not decrease cooling loads and operational carbon enough to justify its' increased embodied carbon. Furthermore, the lower embodied impact of double glazing did not outweigh the increased operational carbon through the heightened U -value. Glazing findings applied to all investigated fenestration types, side glazing, secondary glazing, and top lighting glazing. For frames, it was found that the best-insulated window frame should be chosen from a WLC perspective.

Atria, layout, and materials influence embodied and operational carbon, and thus WLC. Atria volume notably impacts the B6 use stage, while glazed fire-rated interior walls increase embodied carbon. This impact could be reduced by using more opaque fire partitions and cellular offices. Although not covered here, a fire safety assessment could optimize the layout to minimize carbon-intensive fire-rated materials. Flooring also affects WLC and sDA, highlighting the need to balance material choices with environmental and daylight goals, as design decisions influence operational and embodied carbon.

FT results show SB had the highest WLC due to demolishing top lighting with no reuse option; BB ranked second due to its complex form, extra floors, and high operational carbon from large atria volume; FB, with its simple form and minimal top lighting, had the lowest WLC.

Investigating daylight provision on each floor revealed no issues complying with minimum thresholds, while high thresholds were unreachable in the FB and SB on the ground and first floor, indicating the daylight standard recommendations might be too strict for transformation projects, even at high opaque reflectance. As occupied grid depth was aligned amongst all FTs, added atria were found to have a greater effect in the BB, whereas they failed to provide enough daylight in the other FTs with their deeper floor plates. Reducing the number of desks from three to two would improve performance, as the occupied area would decrease. However, in this study, reaching the thresholds was not possible if the daylight grid were to be defined for more spaces. This suggests that FTs with shallow floor plates, such as the BB, may be generally easier to transform into offices, whereas deep floor plate typologies, like the SB, may fit other uses, like cultural, workshop, or recreational functions that do not require view out. These findings further highlighted the importance of assessing sDA compliance at the room level. Building-level optimization was found to obscure underperformance on lower floors. As suggested by the literature, allowing for a greater WWR on the ground floor is often advantageous compared to upper floors. However, this study applied the same WWR across all facades for simplicity.

While all optimized design combinations met the BR18 limit for GWP life cycle carbon emissions with current boundary conditions, only a subset would comply with the stricter BR25 targets, as environmental impacts for A4-5 LCS must be included. This would mean that the SB would only comply when reaching minimum daylight provisions, while the BB could reach both minimum and medium thresholds. The FB would be the only FT to reach BR25 limits while also reaching all three daylight provision threshold levels. The FB could also reach BR27 limits simultaneously with minimum and medium daylight provisions if boundary conditions do not change further.

Consequently, while results from this study were found to comply with future limits, compliance is not ensured, as required LCS for BR25 limits were excluded, and other future boundary conditions are uncertain. This finding suggests that daylight thresholds may be too strict for future GWP limits, especially for FTs with high WRRs and in new buildings, as carbon-intensive building parts, like the structural system, were existing and thus omitted from this study.

5.2 Limitations and Challenges

The architectural concept used simplifications to define the study boundaries, which, in some cases, influenced the results. The design process for each formal typology assumed the buildings were not historically protected. This allowed compliance with lower BR18 U-values and energy frame demands for buildings undergoing a change in use without cultural heritage status. If the buildings were protected, higher *U*-values would be accepted, increasing operational carbon. Embodied carbon may also decrease due to fewer materials needed to meet lower energy requirements.

Historical protection, being subjective and assessed case by case, was excluded to avoid complexity. Assuming minimal protection represents a worst-case scenario for operational and embodied carbon and allows greater design freedom in choosing parameters varied in MOO. Four key factors were excluded from the LCA scope, which may have influenced the results. First, the study relied mainly on non-specific EPDs rather than product-specific data. While this allowed for generalization, it may have reduced the accuracy of impact calculations for certain building elements.

Second, the assessment did not include the embodied impacts of installing and maintaining HVAC systems, focusing instead on the envelope and daylight-related design parameters. Notably, the SB typology experienced multiple overheating cases, which had to be filtered out during data handling. The overheating hours suggested that the simplified HVAC system used in all FTs was undersized for SB and oversized for BB, which showed no overheating. Including HVAC systems would likely have affected the WLC, as they are major contributors to environmental impacts.

Third, fenestration impacts were calculated based on glazing replacement only, excluding frames, due to the 50-year lifespan assumed in the EPDs. Glass and frame thickness were kept constant despite increases in WWR, which is unrealistic. Excluding frame replacement and variations in thickness led to an underestimation of the WLC impacts of windows, particularly frames. Including these factors would have placed more weight on fenestration systems and their influence on daylighting strategies.

Fourth, integrating environmental and daylight simulations introduced a challenge of aligning input properties. The radiance properties varied from EPD properties. Alignment was possible but required additional programs and time to produce aligned radiance and EPD data. The simplification introduced a small variation between simulated and actual glazing properties. The variations in T_{vis} were between 1 % and 4 %, and no clear trend was observed in MOO due to this simplification. Furthermore, the EPDs for the window frame components were generic values that did not correspond to the exact *U*-values of the chosen frames from ISO 10077-2. This variation between input properties might be less critical in early project phases but could significantly impact the results of detailed LCAs.

The daylight simulations included simplifications to reduce computation time. Furniture was excluded to align with Danish BR, which do not require furniture to be included (BR18, 2018, § 379 - § 381). In contrast, LM-83-12 and LEED do (IES, 2012; LEED, 2024). Reflectances were found to impact daylight performance significantly, especially for deeper floor plates. There were challenges in choosing reflectance from the given ranges in EN 17037 and aligning the set reflectance with material properties in an EPD. The tests revealed that all FTs failed to reach medium and high thresholds when utilizing the recommended base reflectance values, even when substantially reducing the daylight grid area. A balance was made between setting a reasonable reflectance for opaque surfaces and defining the occupied area. This balance presented another challenge: defining the occupied area to establish the daylight grid. The definition of “regularly occupied spaces” varied in standards, regulations, and certification systems, significantly affecting how buildings are transformed and their materiality.

5.3 Further Research

As this study investigated the challenges in aligning environmental and daylight performance, several avenues arose for further investigation. On an architectural level, varying atria, room height, and performing parametric atria and office layouts that balance WLC and sDA could be investigated.

Future studies could investigate the link between building material reflectance and environmental impact because interior finishes influenced WLC, and selecting surface reflectance greatly affected daylighting in each FT. Another large percentage of WLC impacts were due to demolishing existing top lighting. Therefore, further research into keeping existing top lighting and investigating secondary glazing or reusing windowpanes is needed, especially in Top lighting-dominated FTs, such as the SB.

Glazing and blinds were significant contributors to varied impacts. Future research is needed to include various shading options and coated glazing options to minimize the environmental impact of shading. Operational carbon contributed the most to WLC. New studies could include HVAC systems in the LCA, as high levels of daylight provision led to overheating in many cases. As installations have a high environmental impact, the influence of daylight provision on it may be substantial.

Future research into operational carbon could investigate environmental impacts if biomass LULUCF is included in district heating emissions in Denmark. This could also be combined with a possible weighting of impact stages according to the impact data certainty. This would mean that the A1-A5 stages would be weighted heavier than the B and C stages due to uncertainty with future scenarios. Future studies could investigate, including manufacturer-specific EPDs, to reach lower LCA results. Glazing and frame impacts could be investigated and compared with manufacturer software. This would also allow for separating frame and glazing impacts more than was found possible in this study.

The MOO results achieved sDA values $> 70\%$, primarily for minimum and medium optimizations. This was caused by the method chosen for MOO: Running MOO to determine the best parameter combinations for each FT involved minimizing LCA and maximizing sDA beyond $50 F_{\text{time}}\%$. The EN 17037 only recommends $50 F_{\text{time}}\%$. Maximizing sDA beyond $50 F_{\text{time}}\%$ made it difficult to achieve limit values. A future study could maximize based on binary compliance (true or false) or ($\%$ of occupied spaces, weighted by area). This would be an optimal metric for assessing building-level compliance and avoids intentionally exceeding $50 F_{\text{time}}\%$ from the standard.

6 Conclusion

This study assessed whether the daylight thresholds in EN 17037 (minimum, medium, and high) can be met while adhering to LCA limit values when transforming three industrial FTs into perimeter office spaces. The focus was on the key challenges in aligning environmental and daylight performance using Denmark as a contextual framework. The study identified complex challenges with integrated building performance due to the interdependence of design parameters, evolving regulations, outdated standards, and material impacts.

Each assessed FT achieves the current BR18 requirements for all daylight provision thresholds. When the minimum threshold is applied, all FTs also meet the upcoming BR25 limit values. At the medium threshold, only BB and FB meet future limits, while at the high threshold, only FB remains compliant. These findings raise questions about whether current daylight thresholds and assessment methods are well suited to transformation projects and whether thresholds in EN 17037 should be revised. Instead of revising EN 17037, it may be relevant to consider differentiated requirements for transformed buildings, such as lower daylight thresholds or higher energy allowances, to encourage transformation and refurbishment projects. Alternativity promoting the use of low-carbon materials, like reused or biobased products, could be an option that would allow for meeting ambitious daylight targets without exceeding carbon limits. This study used standard industry materials with a ten percent contingency, suggesting that more progressive material choices could offer additional flexibility.

A positive trend shows that higher sDA illuminance levels tend to have higher GWP, driven by increased glazing area and energy demand. Adding windows improves daylight but also increases embodied carbon, even with low-impact insulation. The opposite is observed with high-impact materials, where increased window areas result in lower WLC emissions. Insulation and façade cladding were major contributors to WLC, whereas glazing types greatly impacted performance.

FTs that feature large top glazing and deep floor plates posed the greatest challenge for balancing building performance criteria. Atria geometry greatly impacted operational carbon due to the form factor and the embodied carbon from fire-rated interior glazing.

The optimal glazing for all FTs was standard clear triple glazing for all new top and side lighting and standard secondary glazing for existing openings, in combination with blinds for all openings and each FT. LowE glazing with blinds reduced B6 but did not compensate for its higher embodied carbon. Literature suggests that LowE glazing is more effective when used without blinds.

The methods from EN 17037 present several challenges. The definition of regularly occupied spaces is not concise and is a highly sensitive parameter that heavily influences building layouts, which in turn shapes both daylight and environmental performance. Additionally, the standard provides ranges for opaque material reflectances, which strongly affect daylight results. This was especially evident in spaces with deep floor plates, where selecting low reflectance values often prevented achieving higher daylight levels. In regards to the specific FTs:

- Sawtooth (SB): SB had the highest WLC due to extensive top lighting requiring demolition. SB achieves minimum and medium daylight levels but is challenged to meet high on floor 0.
- Barrel (BB): Ranked second highest in WLC due to embodied carbon from its complex form and additional floor levels. It successfully achieved all minimum, medium, and high thresholds.
- Flat (FB): FB had the lowest WLC due to its simple form and minimal top lighting. FB meets minimum and medium daylight thresholds but underperforms on floors 0 and 1 for high levels.

Lastly, these conclusions apply specifically to transformation and renovation projects in the Nordics and may not extend to new construction, where outcomes can differ significantly.

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Appendix A – Method

Table 37: Formal typologies transformation examples. Legend: T = Transformed, PT = Partially transformed; S = Sawtooth roof, B = Barrel Roof, P = Pitched Roof, RS = Ridge Skylight, F = Flat roof,

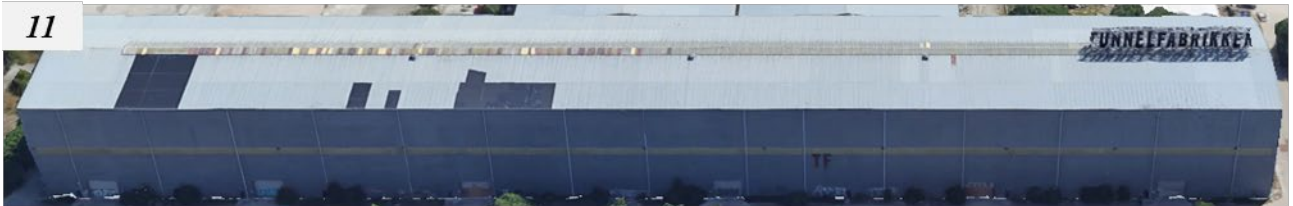
	Name	City	Former Function	Roof	Floors	Façade Material	Transformation Status	Reference
Single Floor, Bi-axial	<i>Dalum Papirfabrikken</i>	Odense	Paper Factory	S	2	Concrete	T – Residential and Offices	1
	<i>Spor 10 (Jernbanebyen)</i>	Copenhagen	Train Maintenance	S	2	Brick	T - Culture	2
	<i>Øksnehallerne</i>	Copenhagen	Cattle Market	S	2	Brick	T - Culture	3
	<i>Lokomotiv værkstedet</i>	Copenhagen	Train Maintenance	S	2	Steel / Brick	T - Culture	4
	<i>Den Hvide Kødby</i>	Copenhagen	Meat Processing	S	2	Concrete	T - Culture	5
	<i>Gabriel Ervervspark</i>	Aalborg	Clothing Factory	S/B/F	1/3/1	Concrete	T - Commercial	6
	<i>Office Lendager</i>	Copenhagen	Train Maintenance	S	1	Concrete / Brick	T - Office	7
Multi-story, Monoaxial	<i>Spinderihallerne</i>	Vejle	Spinning	B	1	Concrete / Brick	T – Culture / Off.	8
	<i>Valby Maskinfabrik</i>	Copenhagen	Machine Production	B, RS	3	Steel / Brick	T – Res. / Comm.	9
	<i>DGI Huset</i>	Aarhus	Workshop	B	3	Concrete	T - Culture	10
	<i>Tunnelfabrikken</i>	Copenhagen	Workshop	P, RS	3	Lightweight Elements	T – Culture	11
	<i>Refshaleøen, svejsehallerne</i>	Copenhagen	Welding	B, RS	3	Concrete; Steel / Brick	PT – Culture / Off.	12
Multi-story, Bi-axial	<i>Filmby</i>	Aarhus	Unknown	B	4	Concrete / Brick	T - Office	13
	<i>Cobe / Gottlieb Paludan Architects Office</i>	Copenhagen	Warehouse	F	2	Concrete / Brick	T - Office	14
	<i>Diplyonhus Arkitema Office</i>	Copenhagen	Grain Storage	F	5	Concrete / Brick	T - Office	15
	<i>Hotel Ottilia / Lagerkælder 3</i>	Copenhagen	Warehouse	F	5	Concrete / Brick	T – Hotel	16
	<i>PLH Office</i>	Copenhagen	Electronics Factory	F	2	Concrete / Brick	T - Office	17

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- 11 www.tunnelfabrikken.dk/fabrik.dk/
- 12 www.refshaleoen.dk/om-refshaleoen/historie/
- 13 www.filmbyaarhus.dk/om-filmby-aarhus/om-filmby-aarhus
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- 16 www.arkitema.com/dk/projekt/hotel-ottilia
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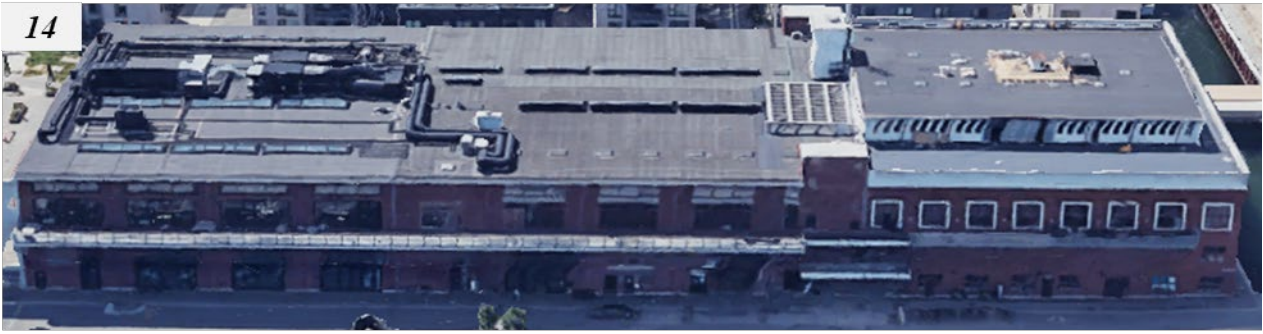


Figure 36: Single Floor, bi-axial building examples. Images taken from Google Earth (2025)



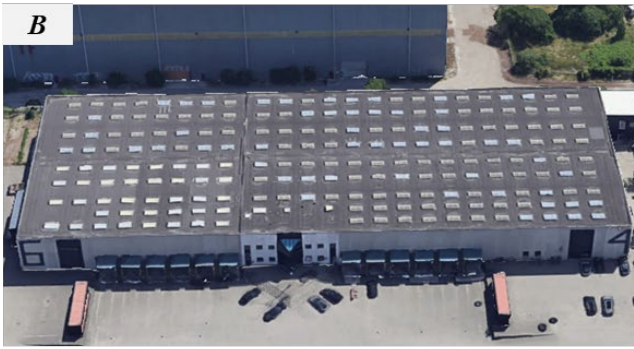
- 9: Valby Maskinfabrik
- 6: Gabriel Ervervspark
- 10: DGI Huset
- 11: Tunnelfabrikken
- 12: Refshaleøen, svejsehallerne
- 13: Filmby

Figure 37: Multi-story, monoaxial building examples. Images taken from Google Earth (2025)



- 14: Cobe / Gottlieb Paludan Architects Office
- 15: Diplyonhus Arkitema Office
- 16: Hotel Ottilia / Lagerkælder 3
- 17: PLH Office

Figure 38: Multi-story, bi-axial building examples. Images taken from Google Earth (2025)



A: Falkevej and Glentevej, Esbjerg
 (www.avantea-global.com/about-us/
 and <https://www.st-plast.dk/>)

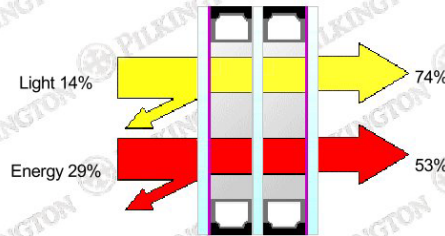
B: WIST, Copenhagen
 (<https://wist.dk/>)

C: MAN, Copenhagen
 (www.everllence.com/)

D: Nordic MV, Aarlborg
 (www.nordicmv.com/)

Figure 39: Flat roof typologies, top lighting layout.. Images taken from Google Earth (2025)

Pilkington Glazing Assemblies



DESCRIPTION

Position	Product	Process	Thickness (nominal) mm	Weight kg/m ²
Pilkington Insulight™ Therm Triple				
Glass 1	Pilkington Optitherm™ S3	Annealed	4.0	
Cavity 1	Argon (90%)		18.0	
Glass 2	Pilkington Optifloat™ Clear	Annealed	4.0	
Cavity 2	Argon (90%)		18.0	
Glass 3	Pilkington Optitherm™ S3	Annealed	4.0	
Product Code	4S(3)-18Ar-4-18Ar-S(3)4		48.0	30.00

PERFORMANCE

Light			Energy		
Transmittance	LT	74%	Direct Transmittance	ET	45%
	UV %	16%	Reflectance	ER	29%
Reflectance Out	LR out	14%	Absorptance	EA	26%
Reflectance In	LR in	14%	Total Transmittance	g	53%
Performance Code			Shading Coefficient Total		0.61
U _g -value/Light/Energy		0.52 / 74 / 53	Shading Coefficient Shortwave		0.52
Ra		96	Sound Reduction	R _w (C;C _{tr}) dB	32 (-1; -4)
The values of some of characteristics are displayed as NPd. This stands for No Performance Determined.			Thermal Transmittance	W/m ² K	0.52

Carbon Footprint

GWP	kgCO ₂ e/m ²	51
Global Warming Potential (GWP) values derived from the Life Cycle Assessment (LCA) that underpins the third-party verified product Environmental Product Declarations (EPDs). They are declared for modules A1 to A3; the scope of the EPDs is cradle-to-grave and module D in accordance with the requirements of Product Category Rules EN 15804:2012+A2:2019/AC:2021 and EN17074:2019. As noted in the EPD, indicators for modules A1 to A3 should not be used without considering indicators for module C.		

Pilkington Spectrum allows you to combine a wide range of products available from Pilkington and determine their key properties such as light transmittance, g value and U value. The program includes restrictions that prevent some combinations being selected that may be considered unwise or impractical. Even with these restrictions, it is still possible to create product combinations that may not be available from your supplier. Please check with your supplier that your chosen product combination is possible, available in the sizes required and in a timescale appropriate to your project. Furthermore, it is essential that you check that your product combination is appropriate for satisfying local, regional, national and other project-specific requirements.

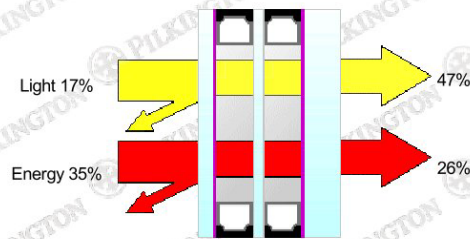
Calculations are made according to EN standards 410 and 673/12898

Pilkington Spectrum Version Denmark:7.4.1

04/03/2025



Figure 40: Pilkington Spectrum side glazing assembly for standard triple glazing. Based on Vefac Standard Rude.



DESCRIPTION

Position	Product	Process	Thickness (nominal) mm	Weight kg/m ²
Pilkington Insulight™ Sun Triple				
Glass 1	Pilkington Suncool™ 60/31 Pro T	Toughened	6.0	
Cavity 1	Argon (90%)		16.0	
Glass 2	Pilkington Optifloat™ Clear	Annealed	4.0	
Cavity 2	Argon (90%)		16.0	
Glass 3	Pilkington Optilam™ Therm S1	Laminated	9.5	
Product Code	6C(61)T-16Ar-4-16Ar-S(1)9.5L		51.5	46.52

PERFORMANCE

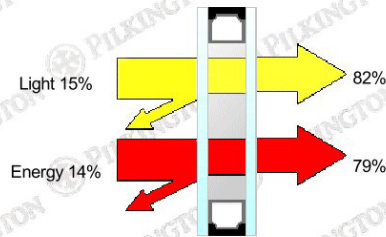
Light			Energy		
Transmittance	LT	47%	Direct Transmittance	ET	21%
	UV %	0%	Reflectance	ER	35%
Reflectance Out	LR out	17%	Absorptance	EA	44%
Reflectance In	LR in	28%	Total Transmittance	g	26%
Performance Code			Shading Coefficient Total		
U _g -value/Light/Energy			0.52 / 47 / 26		
Ra			89		
The values of some of characteristics are displayed as NPd. This stands for No Performance Determined.					
Sound Reduction			R _w (C;C _{tr}) dB	40 (-2; -7)	
Thermal Transmittance			W/m ² K	0.52	

Carbon Footprint		
GWP	kgCO ₂ e/m ²	96
Global Warming Potential (GWP) values derived from the Life Cycle Assessment (LCA) that underpins the third-party verified product Environmental Product Declarations (EPDs). They are declared for modules A1 to A3; the scope of the EPDs is cradle-to-grave and module D in accordance with the requirements of Product Category Rules EN 15804:2012+A2:2019/AC:2021 and EN17074:2019. As noted in the EPD, indicators for modules A1 to A3 should not be used without considering indicators for module C.		
Pilkington Spectrum allows you to combine a wide range of products available from Pilkington and determine their key properties such as light transmittance, g value and U value. The program includes restrictions that prevent some combinations being selected that may be considered unwise or impractical. Even with these restrictions, it is still possible to create product combinations that may not be available from your supplier. Please check with your supplier that your chosen product combination is possible, available in the sizes required and in a timescale appropriate to your project. Furthermore, it is essential that you check that your product combination is appropriate for satisfying local, regional, national and other project-specific requirements.		

Calculations are made according to EN standards 410 and 673/12898
 Pilkington Spectrum Version Denmark:7.4.1 04/03/2025



Figure 41: Pilkington Spectrum side glazing assembly. Triple glazing, LowE. Based on Velfac SKN154, solrude.


DESCRIPTION

Position	Product	Process	Thickness (nominal) mm	Weight kg/m ²
Pilkington Insulight™ Therm				
Glass 1	Pilkington Optifloat™ Clear	Annealed	4.0	
Cavity 1	Argon (90%)		16.0	
Glass 2	Pilkington Optifloat™ Clear	Annealed	4.0	
Product Code	4-16Ar-4		24.0	20.00

PERFORMANCE

Light			Energy		
Transmittance	LT	82%	Direct Transmittance	ET	76%
	UV %	55%	Reflectance	ER	14%
Reflectance Out	LR out	15%	Absorptance	EA	10%
Reflectance In	LR in	15%	Total Transmittance	g	79%
Performance Code			Shading Coefficient Total		0.91
U _g -value/Light/Energy		2.62 / 82 / 79	Shading Coefficient Shortwave		0.87
Ra		98	Sound Reduction	R _w (C;C _{tr}) dB	31 (-2; -5)
The values of some of characteristics are displayed as NPD. This stands for No Performance Determined.			Thermal Transmittance	W/m ² K	2.62

Carbon Footprint

GWP kgCO₂e/m² 32

Global Warming Potential (GWP) values derived from the Life Cycle Assessment (LCA) that underpins the third-party verified product Environmental Product Declarations (EPDs). They are declared for modules A1 to A3; the scope of the EPDs is cradle-to-grave and module D in accordance with the requirements of Product Category Rules EN 15804:2012+A2:2019/AC:2021 and EN17074:2019. As noted in the EPD, indicators for modules A1 to A3 should not be used without considering indicators for module C.

Pilkington Spectrum allows you to combine a wide range of products available from Pilkington and determine their key properties such as light transmittance, g value and U value. The program includes restrictions that prevent some combinations being selected that may be considered unwise or impractical. Even with these restrictions, it is still possible to create product combinations that may not be available from your supplier. Please check with your supplier that your chosen product combination is possible, available in the sizes required and in a timescale appropriate to your project. Furthermore, it is essential that you check that your product combination is appropriate for satisfying local, regional, national and other project-specific requirements.

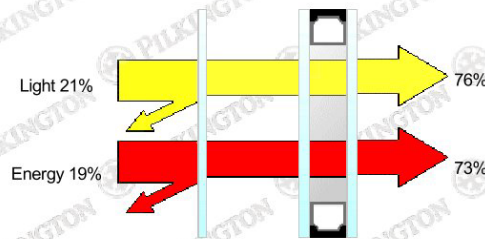
Calculations are made according to EN standards 410 and 673/12898

Pilkington Spectrum Version Denmark:7.4.1

04/03/2025



Figure 42: Pilkington Spectrum side glazing assembly. Double glazing, standard. Based on Velfac Edge.



DESCRIPTION

Position	Product	Process	Thickness (nominal) mm	Weight kg/m ²
Pilkington Optifloat™ Clear + Pilkington Insulight™ Therm				
Glass 1	Pilkington Optifloat™ Clear	Annealed	3.0	
Cavity 1	Air		40.0	
Glass 2	Pilkington Optifloat™ Clear	Annealed	4.0	
Cavity 2	Argon (90%)		16.0	
Glass 3	Pilkington Optifloat™ Clear	Annealed	4.0	
Product Code	3+40+4-16Ar-4		67.0	27.50

PERFORMANCE

Light			Energy		
Transmittance	LT	76%	Direct Transmittance	ET	67%
	UV %	46%	Reflectance	ER	19%
Reflectance Out	LR out	21%	Absorptance	EA	14%
Reflectance In	LR in	21%	Total Transmittance	g	73%
Performance Code			Shading Coefficient Total		0.84
U _g -value/Light/Energy		1.7 / 76 / 73	Shading Coefficient Shortwave		0.78
Ra		98	Sound Reduction	R _w (C; C _{tr}) dB	NPD
The values of some of characteristics are displayed as NPD. This stands for No Performance Determined.			Thermal Transmittance	W/m ² K	1.7

Carbon Footprint

GWP	kgCO ₂ e/m ²	49
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Global Warming Potential (GWP) values derived from the Life Cycle Assessment (LCA) that underpins the third-party verified product Environmental Product Declarations (EPDs). They are declared for modules A1 to A3; the scope of the EPDs is cradle-to-grave and module D in accordance with the requirements of Product Category Rules EN 15804:2012+A2:2019/AC:2021 and EN17074:2019. As noted in the EPD, indicators for modules A1 to A3 should not be used without considering indicators for module C.

Pilkington Spectrum allows you to combine a wide range of products available from Pilkington and determine their key properties such as light transmittance, g value and U value. The program includes restrictions that prevent some combinations being selected that may be considered unwise or impractical. Even with these restrictions, it is still possible to create product combinations that may not be available from your supplier. Please check with your supplier that your chosen product combination is possible, available in the sizes required and in a timescale appropriate to your project. Furthermore, it is essential that you check that your product combination is appropriate for satisfying local, regional, national and other project-specific requirements.

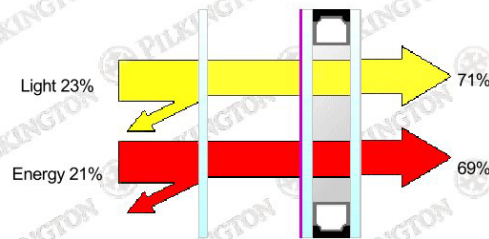
Calculations are made according to EN standards 410 and 673/12898

Pilkington Spectrum Version Denmark:7.4.1

07/03/2025



Figure 43: Pilkington Spectrum secondary glazing assembly. Double glazing, standard. Based on Velfac Edge.



DESCRIPTION

Position	Product	Process	Thickness (nominal) mm	Weight kg/m ²
Pilkington Optifloat™ Clear + Pilkington Insulight™ Therm				
Glass 1	Pilkington Optifloat™ Clear	Annealed	3.0	
Cavity 1	Air		40.0	
Glass 2	Pilkington K Glass™ N	Annealed	4.0	
Cavity 2	Argon (90%)		16.0	
Glass 3	Pilkington Optiwhite™	Annealed	4.0	
Product Code	3+40+KN4-16Ar-4w		67.0	27.50

PERFORMANCE

Light			Energy		
Transmittance	LT	71%	Direct Transmittance	ET	60%
	UV %	42%	Reflectance	ER	21%
Reflectance Out	LR out	23%	Absorptance	EA	19%
Reflectance In	LR in	23%	Total Transmittance	g	69%
Performance Code			Shading Coefficient Total		0.79
U _g -value/Light/Energy		1.22 / 71 / 69	Shading Coefficient Shortwave		0.69
Ra		99	Sound Reduction	R _w (C;C _f) dB	NPD
The values of some of characteristics are displayed as NPD. This stands for No Performance Determined.			Thermal Transmittance	W/m ² K	1.22

Carbon Footprint

GWP	kgCO ₂ e/m ²	56
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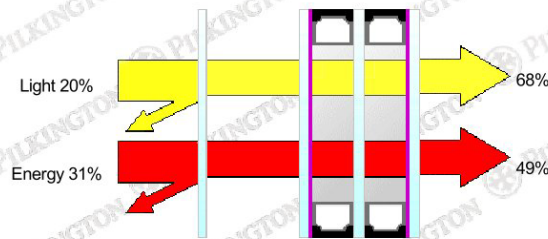
Global Warming Potential (GWP) values derived from the Life Cycle Assessment (LCA) that underpins the third-party verified product Environmental Product Declarations (EPDs). They are declared for modules A1 to A3; the scope of the EPDs is cradle-to-grave and module D in accordance with the requirements of Product Category Rules EN 15804:2012+A2:2019/AC:2021 and EN17074:2019. As noted in the EPD, indicators for modules A1 to A3 should not be used without considering indicators for module C.

Additional Values

Bullet Resistance	NPD	Burglar Resistance	NPD+NPD+NPD
Explosion Resistance	NPD	External Fire Performance	NPD
Load Resistance (MPa)	45+45+45	Pendulum Body Impact Resistance	NPD
Reaction to Fire	NPD	Resistance to Fire	NPD
Resistance to Temperature Differentials (K)	40+40+40		

Pilkington Spectrum allows you to combine a wide range of products available from Pilkington and determine their key properties such as light transmittance, g value and U value. The program includes restrictions that prevent some combinations being selected that may be considered unwise or impractical. Even with these restrictions, it is still possible to create product combinations that may not be available from your supplier. Please check with your supplier that your chosen product combination is possible, available in the sizes required and in a timescale appropriate to your project. Furthermore, it is essential that you check

Figure 44: Pilkington Spectrum secondary glazing assembly. Double glazing. Based on Bøjsø.



DESCRIPTION

Position	Product	Process	Thickness (nominal) mm	Weight kg/m ²
Pilkington Optifloat™ Clear + Pilkington Insulight™ Therm Triple				
Glass 1	Pilkington Optifloat™ Clear	Annealed	3.0	
Cavity 1	Air		40.0	
Glass 2	Pilkington Optitherm™ S3	Annealed	4.0	
Cavity 2	Argon (90%)		18.0	
Glass 3	Pilkington Optifloat™ Clear	Annealed	4.0	
Cavity 3	Argon (90%)		18.0	
Glass 4	Pilkington Optitherm™ S3	Annealed	4.0	
Product Code	3+40+S(3)4-18Ar-4-18Ar-S(3)4		91.0	37.50

PERFORMANCE

Light			Energy		
Transmittance	LT	68%	Direct Transmittance	ET	41%
	UV %	14%	Reflectance	ER	31%
Reflectance Out	LR out	20%	Absorptance	EA	28%
Reflectance In	LR in	19%	Total Transmittance	g	49%
Performance Code			Shading Coefficient Total	0.56	
U _g -value/Light/Energy		0.47 / 68 / 49	Shading Coefficient Shortwave	0.47	
Ra		96	Sound Reduction	R _w (C;C _{tr}) dB	NPD
The values of some of characteristics are displayed as NPD. This stands for No Performance Determined.			Thermal Transmittance	W/m ² K	0.47

Carbon Footprint

GWP kgCO₂e/m² 50

Global Warming Potential (GWP) values derived from the Life Cycle Assessment (LCA) that underpins the third-party verified product Environmental Product Declarations (EPDs). They are declared for modules A1 to A3; the scope of the EPDs is cradle-to-grave and module D in accordance with the requirements of Product Category Rules EN 15804:2012+A2:2019/AC:2021 and EN17074:2019. As noted in the EPD, indicators for modules A1 to A3 should not be used without considering indicators for module C.

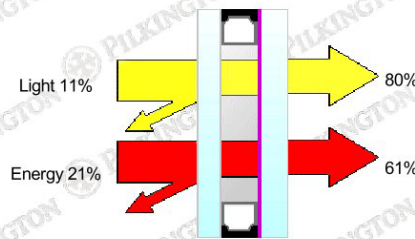
Pilkington Spectrum allows you to combine a wide range of products available from Pilkington and determine their key properties such as light transmittance, g value and U value. The program includes restrictions that prevent some combinations being selected that may be considered unwise or impractical. Even with these restrictions, it is still possible to create product combinations that may not be available from your supplier. Please check with your supplier that your chosen product combination is possible, available in the sizes required and in a timescale appropriate to your project. Furthermore, it is essential that you check that your product combination is appropriate for satisfying local, regional, national and other project-specific requirements.

Calculations are made according to EN standards 410 and 673/12898

Pilkington Spectrum Version Denmark:7.4.1

07/03/2025

Figure 45: Pilkington Spectrum secondary glazing assembly. Triple glazing, standard. Based on Velfac Standard Rude.


DESCRIPTION

Position	Product	Process	Thickness (nominal) mm	Weight kg/m ²
Pilkington Insulight™ Phon				
Glass 1	Pilkington Optiphon™	Laminated	6.8	
Cavity 1	Argon (90%)		16.0	
Glass 2	Pilkington Optilam™ Therm S3	Laminated	8.8	
Product Code	6.8Lp-16Ar-S(3)8.8L		31.6	36.52

PERFORMANCE

Light			Energy		
Transmittance	LT	80%	Direct Transmittance	ET	51%
	UV %	0%	Reflectance	ER	21%
Reflectance Out	LR out	11%	Absorptance	EA	28%
Reflectance In	LR in	11%	Total Transmittance	g	61%
Performance Code			Shading Coefficient Total		0.7
U _g -value/Light/Energy		1.10 / 80 / 61	Shading Coefficient Shortwave		0.59
Ra		96	Sound Reduction	R _w (C;C _{tr}) dB	NPD
The values of some of characteristics are displayed as NPD. This stands for No Performance Determined.			Thermal Transmittance	W/m ² K	1.10

Carbon Footprint

GWP kgCO₂e/m² 73

Global Warming Potential (GWP) values derived from the Life Cycle Assessment (LCA) that underpins the third-party verified product Environmental Product Declarations (EPDs). They are declared for modules A1 to A3; the scope of the EPDs is cradle-to-grave and module D in accordance with the requirements of Product Category Rules EN 15804:2012+A2:2019/AC:2021 and EN17074:2019. As noted in the EPD, indicators for modules A1 to A3 should not be used without considering indicators for module C.

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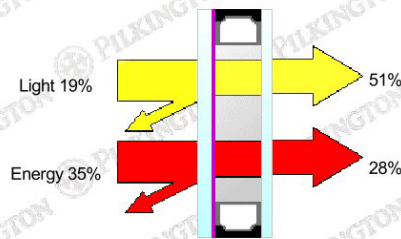
Calculations are made according to EN standards 410 and 673/12898

Pilkington Spectrum Version Denmark:7.4.1

07/03/2025



Figure 46: Pilkington Spectrum top glazing assembly. Double glazing, clear. Based on Velux T Clear Double.



DESCRIPTION

Position	Product	Process	Thickness (nominal) mm	Weight kg/m ²
Pilkington Insulight™ Sun				
Glass 1	Pilkington Suncool™ Blue 50/27 Pro T	Toughened	6.0	
Cavity 1	Argon (90%)		20.0	
Glass 2	Pilkington Optifloat™ Clear	Toughened	4.0	
Product Code	6Cb(50)T-20Ar-4T		30.0	25.00

PERFORMANCE

Light			Energy		
Transmittance	LT	51%	Direct Transmittance	ET	26%
	UV %	7%	Reflectance	ER	35%
Reflectance Out	LR out	19%	Absorptance	EA	39%
Reflectance In	LR in	18%	Total Transmittance	g	28%
Performance Code			Shading Coefficient Total		0.32
U _g -value/Light/Energy	1.07 / 51 / 28		Shading Coefficient Shortwave		0.3
Ra	95		Sound Reduction	R _w (C;C _{tr}) dB	34 (-2; -5)
The values of some of characteristics are displayed as NPD. This stands for No Performance Determined.			Thermal Transmittance	W/m ² K	1.07

Carbon Footprint

GWP kgCO₂e/m² 56

Global Warming Potential (GWP) values derived from the Life Cycle Assessment (LCA) that underpins the third-party verified product Environmental Product Declarations (EPDs). They are declared for modules A1 to A3; the scope of the EPDs is cradle-to-grave and module D in accordance with the requirements of Product Category Rules EN 15804:2012+A2:2019/AC:2021 and EN17074:2019. As noted in the EPD, indicators for modules A1 to A3 should not be used without considering indicators for module C.

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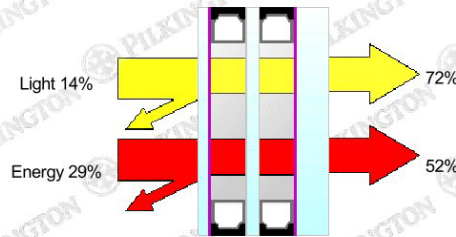
Calculations are made according to EN standards 410 and 673/12898

Pilkington Spectrum Version Denmark:7.4.1

07/03/2025



Figure 47: Pilkington Spectrum top glazing assembly. Triple glazing, LowE. Based on Velux T Sun Double.



DESCRIPTION

Position	Product	Process	Thickness (nominal) mm	Weight kg/m ²
Pilkington Insulight™ Protect Triple				
Glass 1	Pilkington Optitherm™ S3	Annealed	4.0	
Cavity 1	Argon (90%)		15.0	
Glass 2	Pilkington Optifloat™ Clear	Annealed	5.0	
Cavity 2	Argon (90%)		15.0	
Glass 3	Pilkington Optilam™ Therm S3	Laminated	10.8	
Product Code	4S(3)-15Ar-5-15Ar-S(3)10.8L		49.8	48.26

PERFORMANCE

Light			Energy		
Transmittance	LT	72%	Direct Transmittance	ET	41%
	UV %	0%	Reflectance	ER	29%
Reflectance Out	LR out	14%	Absorptance	EA	30%
Reflectance In	LR in	14%	Total Transmittance	g	52%
Performance Code			Shading Coefficient Total		0.6
U _g -value/Light/Energy	0.60 / 72 / 52		Shading Coefficient Shortwave		0.47
Ra	95		Sound Reduction	R _w (C; C _{tr}) dB	NPD
The values of some of characteristics are displayed as NPD. This stands for No Performance Determined.					
Carbon Footprint			Thermal Transmittance		
GWP	kgCO ₂ e/m ²	84	W/m ² K		

Carbon Footprint

Global Warming Potential (GWP) values derived from the Life Cycle Assessment (LCA) that underpins the third-party verified product Environmental Product Declarations (EPDs). They are declared for modules A1 to A3; the scope of the EPDs is cradle-to-grave and module D in accordance with the requirements of Product Category Rules EN 15804:2012+A2:2019/AC:2021 and EN17074:2019. As noted in the EPD, indicators for modules A1 to A3 should not be used without considering indicators for module C.

Pilkington Spectrum allows you to combine a wide range of products available from Pilkington and determine their key properties such as light transmittance, g value and U value. The program includes restrictions that prevent some combinations being selected that may be considered unwise or impractical. Even with these restrictions, it is still possible to create product combinations that may not be available from your supplier. Please check with your supplier that your chosen product combination is possible, available in the sizes required and in a timescale appropriate to your project. Furthermore, it is essential that you check that your product combination is appropriate for satisfying local, regional, national and other project-specific requirements.

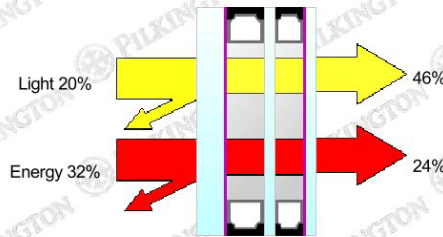
Calculations are made according to EN standards 410 and 673/12898

Pilkington Spectrum Version Denmark:7.4.1

07/03/2025



Figure 48: Pilkington Spectrum top glazing assembly. Triple glazing, clear. Based on Velux T Clear Triple.



DESCRIPTION

Position	Product	Process	Thickness (nominal) mm	Weight kg/m ²
Pilkington Insulight™ Sun Triple				
Glass 1	Pilkington Suncool Optilam™ 50/25	Laminated	8.8	
Cavity 1	Argon (90%)		16.0	
Glass 2	Pilkington Optifloat™ Clear	Annealed	4.0	
Cavity 2	Argon (90%)		12.0	
Glass 3	Pilkington Optitherm™ S3 Pro T	Toughened	4.0	
Product Code	8.8LC(50)-16Ar-4-12Ar-S(3)4T		44.8	40.76

PERFORMANCE

Light			Energy		
Transmittance	LT	46%	Direct Transmittance	ET	21%
	UV %	0%	Reflectance	ER	32%
Reflectance Out	LR out	20%	Absorptance	EA	47%
Reflectance In	LR in	21%	Total Transmittance	g	24%
Performance Code			Shading Coefficient Total		0.28
U _g -value/Light/Energy		0.60 / 46 / 24	Shading Coefficient Shortwave		0.24
Ra		91	Sound Reduction	R _w (C; C _{tr}) dB	NPD
The values of some of characteristics are displayed as NPD. This stands for No Performance Determined.			Thermal Transmittance	W/m ² K	0.60

Carbon Footprint		
GWP	kgCO ₂ e/m ²	81
Global Warming Potential (GWP) values derived from the Life Cycle Assessment (LCA) that underpins the third-party verified product Environmental Product Declarations (EPDs). They are declared for modules A1 to A3; the scope of the EPDs is cradle-to-grave and module D in accordance with the requirements of Product Category Rules EN 15804:2012+A2:2019/AC:2021 and EN17074:2019. As noted in the EPD, indicators for modules A1 to A3 should not be used without considering indicators for module C.		
Pilkington Spectrum allows you to combine a wide range of products available from Pilkington and determine their key properties such as light transmittance, g value and U value. The program includes restrictions that prevent some combinations being selected that may be considered unwise or impractical. Even with these restrictions, it is still possible to create product combinations that may not be available from your supplier. Please check with your supplier that your chosen product combination is possible, available in the sizes required and in a timescale appropriate to your project. Furthermore, it is essential that you check that your product combination is appropriate for satisfying local, regional, national and other project-specific requirements.		

Calculations are made according to EN standards 410 and 673/12898
 Pilkington Spectrum Version Denmark:7.4.1 07/03/2025



Figure 49: Pilkington Spectrum top glazing assembly. Triple glazing, LowE. Based on Velux T Sun Triple.

Matlab Scripts for Scatter Plots

```
clear; clc;
filePath = "filepath";
sheetName = "Sheet";
xVar = "LCA";
yVar = "x100ETM"; % varied x100ETM, x300ETM, x500ETM
groupVar = "TD"; % varied TD, WWR, SGL, Frame, SecGl, TGl

% Custom figure size and colors
figWidth = 700; % in pixels
figHeight = 500;
customColors = ["#97A6B4"; "#FFBB5A"; "#CB7652"; "#7C9D96"; "#C96763"];

% Load data
dataTable = readtable(filePath, 'Sheet', sheetName);

% Extract x, y, and grouping variable
x = dataTable.(xVar);
y = dataTable.(yVar)*100;
groupData = dataTable.(groupVar);

% Normalize and convert group data to string (used for consistency)
if isnumeric(groupData)
    groupData = string(round(groupData, 2)); % Useful for continuous WWR
else
    groupData = string(groupData);
end

% Unique categories in group variable
categories = unique(groupData);
nColors = numel(customColors);
nGroups = numel(categories);

% Create Figure
figure('Position', [200, 200, figWidth, figHeight]);
hold on;

for i = 1:nGroups
    idx = groupData == categories(i);
    colorIdx = mod(i-1, nColors) + 1;
    scatter(x(idx), y(idx), 30, 'filled', ...
        'MarkerFaceColor', customColors(colorIdx), ...
        'DisplayName', categories(i));
    xlim([5 7.5])
    ylim([0 100])
    ytickformat('percentage')
end

% Add horizontal line at y = 50
hold on;
yline(50, '--r');

% Plot formatting
xlabel(xVar + " [kg CO2 eq / m2 / y]", 'FontSize', 12);
ylabel("sDA" + " (" + yVar + ")", 'FontSize', 12);
%title("Scatter Plot of " + xVar + " vs " + yVar + " grouped by " + groupVar, 'FontSize', 14);
legend('Location', 'SouthOutside');
grid on;
```

Figure 50: MATLAB code scatter plots filtered by parameter

Matlab Scripts for Optimized Data Filter and Sorting

```
clear; clc;
filename = 'filepath';
sheetname = 'Sheet';
opts = detectImportOptions('File.xlsx', 'Sheet', 'sheet');
data = readtable('File.xlsx', opts, 'Sheet', 'sheet');

% Settings
maximize = {'x300ET', 'x100ETM'};
minimize = {'LCA'};

% Normalizing
fprintf('\n--- Normalizing Outputs ---\n');
for i = 1:length(maximize)
    col = maximize{i};
    data.[col '_score'] = (data.(col) - min(data.(col))) ./ (max(data.(col)) - min(data.(col)));
end

for i = 1:length(minimize)
    col = minimize{i};
    data.[col '_score'] = 1 - (data.(col) - min(data.(col))) ./ (max(data.(col)) - min(data.(col)));
end

normalizedMatrix = data(:, [strcat(maximize, '_score'), strcat(minimize, '_score')]);
disp('Normalized Score Matrix:');
disp(normalizedMatrix);

% Weighting
numOther = length(maximize);
weight_LCA = 0.5;
weight_other = (1 - weight_LCA) / numOther;

scoreCols = [strcat(minimize, '_score'), strcat(maximize, '_score')];
weights = [weight_LCA, repmat(weight_other, 1, numOther)];

% Weighted Composite Score
data.Composite_Score = zeros(height(data), 1);
for i = 1:length(scoreCols)
    data.Composite_Score = data.Composite_Score + weights(i) * data.(scoreCols{i});
end

fprintf('\n--- Composite Scores Calculated ---\n');
disp(data(:, {'Composite_Score'}));

% Split Data
if ~any(strcmp('LVL', data.Properties.VariableNames))
    error('Column A ("LVL") must be named "LVL" in the dataset.');
```

```
end

levels = {'LOW', 'MED', 'HIGH'};

for i = 1:length(levels)
    level = levels{i};
    fprintf('\n--- Top 5 Designs for LVL: %s ---\n', level);
    subset = data(strcmpi(data.LVL, level), :);
    sortedSubset = sortrows(subset, 'Composite_Score', 'descend');
    disp(sortedSubset(1:min(10, height(sortedSubset)), :));
end

% Optional: Save full sorted data
writetable(data, 'ranked_designs_full.xlsx');
```

Figure 51: MATLAB code scoring of parameter combinations

Matlab Script for Creating Parallel Coordinate Plots

```
clear; clc;
tbl = readtable('filepath','Sheet', 'Sheet');
head(tbl)

% Remove other levels if needed
tbl(tbl.LVL == "MED" | tbl.LVL == "HIGH", :) = [];

% Set categorical categories
tbl.LVL = categorical(tbl.LVL, {'MIN','MED','HIGH'}, 'Ordinal', true);
tbl.TD = categorical(tbl.TD);
tbl.WWR = categorical(tbl.WWR);
tbl.SG1 = categorical(tbl.SG1);
tbl.SecG1 = categorical(tbl.SecG1);
tbl.TG1 = categorical(tbl.TG1);

% Plot and set figure size
p = parallelplot(tbl);
p.Jitter = 0.1;
p.Title = 'Barrel Roof';
fig=gcf;
fig.Position(3:4)=[1500,400];

% Grouping - change to investigate other impacts
p.GroupVariable = 'LVL';

% Set linewidth
p.LineWidth = 2; % Adjust as needed
colororder(["#97A6B4";"#FFB5A";"#CB7652";"#7C9D96";"#C96763";])
```

Figure 52: MATLAB code parallel plot for top five parameter combinations per FT

LCA Building Elements

Table 38: LCA data from LCAByg [kg CO₂ eq/m² (material)/year]. Data with * is included in LCAByg based on EPDs and the OneClick LCA workflow. Building part names from LCAByg are indicated under the bold name of the building part. The number of replacements during the building's 50-year service life are shown under Repl.

Building Part Name	Repl.	GWP sum kgCO₂eq.	GWP A1-3 kgCO₂eq.	GWP B4 kgCO₂eq.	GWP C3 kgCO₂eq.	GWP C4 kgCO₂eq.	GWP D kgCO₂eq.
Deck, wood elements		1.79E-01	-8.19E-01	0.00E+00	9.97E-01	7.59E-04	-5.12E-01
Dæk, træelement 0,38/6,0 m		1.79E-01	-8.19E-01	0.00E+00	9.97E-01	7.59E-04	-5.12E-01
• Konstruktionstræ af fyr og gran, Savede og tørrede (Forbrænding EoL)	0	4.80E-02	-6.80E-01	0.00E+00	7.28E-01	0.00E+00	-3.71E-01
• Krydsfiner, ubehandlet (Forbrænding EoL)	0	5.18E-02	-2.16E-01	0.00E+00	2.67E-01	0.00E+00	-1.41E-01
• Mineraluld, alm.	0	7.87E-02	7.66E-02	0.00E+00	1.37E-03	7.59E-04	0.00E+00
Flooring		5.44E-01	8.20E-02	0.00E+00	4.29E-01	3.25E-02	-1.18E-01
Gulv, parket, svømmende		5.44E-01	8.20E-02	0.00E+00	4.29E-01	3.25E-02	-1.18E-01
• Afretningslag, cementbaseret	0	3.81E-01	3.52E-01	0.00E+00	0.00E+00	2.88E-02	0.00E+00
• EPS isolering til lofter / gulve og kælderydervæg / terrændæk 040	0	6.89E-03	3.23E-03	0.00E+00	0.00E+00	3.66E-03	-1.93E-03
• Trægulv, stavparket, 22 mm	0	1.56E-01	-2.74E-01	0.00E+00	4.29E-01	0.00E+00	-1.16E-01
Ceilings		2.20E-01	1.08E-01	1.10E-01	1.27E-03	6.61E-04	-3.31E-02
Loft, nedhængt demonterbart systemloft		2.20E-01	1.08E-01	1.10E-01	1.27E-03	6.61E-04	-3.31E-02
• Mineraluld, trykfast til tagsystem	1	1.29E-01	6.29E-02	6.47E-02	1.19E-03	6.61E-04	0.00E+00
• Stål, valsede profiler og plader	1	9.01E-02	4.50E-02	4.51E-02	7.38E-05	0.00E+00	-3.31E-02
Glazed int. wall		1.48E+00	7.60E-01	6.99E-01	8.16E-03	1.63E-02	-8.38E-02
Indvendig glasvæg		1.48E+00	7.60E-01	6.99E-01	8.16E-03	1.63E-02	-8.38E-02
• Aluminiumsprofil	0	8.54E-02	8.54E-02	0.00E+00	0.00E+00	5.46E-06	-6.61E-02
• EPDM-tætning til aluminiumsprofil	1	4.93E-02	8.35E-03	2.47E-02	8.16E-03	8.15E-03	-1.76E-02
• Glas 4 mm	1	1.35E+00	6.66E-01	6.75E-01	0.00E+00	8.18E-03	0.00E+00
Glazed int. wall (atrium, fire rated)		2.45E+00	1.25E+00	1.17E+00	8.16E-03	2.21E-02	-1.00E-01
Indvendig glasvæg (EI30)		2.45E+00	1.25E+00	1.17E+00	8.16E-03	2.21E-02	-1.00E-01
Aluminiumsprofil	0	1.07E-01	1.07E-01	0.00E+00	0.00E+00	6.82E-06	-8.27E-02
• EPDM-tætning til aluminiumsprofil	1	4.93E-02	8.35E-03	2.47E-02	8.16E-03	8.15E-03	-1.76E-02
• Glas 4 mm	1	2.29E+00	1.13E+00	1.15E+00	0.00E+00	1.39E-02	0.00E+00
Opaque int. wall		2.14E-01	-1.31E-01	0.00E+00	3.36E-01	8.87E-03	-1.74E-01
Midterdel, træskelet, ikke-bærende, træfiber		8.69E-02	-2.49E-01	0.00E+00	3.36E-01	0.00E+00	-1.74E-01
• Konstruktionstræ af fyr og gran, Savede og tørrede (Forbrænding EoL)	0	6.77E-03	-9.59E-02	0.00E+00	1.03E-01	0.00E+00	-5.23E-02
• Træfiberisolering	0	8.01E-02	-1.53E-01	0.00E+00	2.33E-01	0.00E+00	-1.21E-01
• Vægside, gipskartonplade 2 lag, akrylmaling		1.27E-01	1.18E-01	0.00E+00	0.00E+00	8.87E-03	-1.13E-04
• Afretningslag, cementbaseret	0	4.77E-02	4.41E-02	0.00E+00	0.00E+00	3.60E-03	0.00E+00
• Gipskartonplade 13 mm, hulplade	0	5.97E-02	5.46E-02	0.00E+00	0.00E+00	5.10E-03	0.00E+00
• Overflade, Facademaling, akryl maling	0	1.61E-02	1.60E-02	0.00E+00	0.00E+00	1.14E-04	-7.16E-05
• Overflade, Facademaling, grunder, dispersion	0	3.48E-03	3.42E-03	0.00E+00	0.00E+00	5.70E-05	-4.11E-05
Existing Roof / demolition		1.20E-02	0.00E+00	0.00E+00	1.17E-02	3.27E-04	-1.07E-03
Midterlag, træelement, ventileret, flade/skrå tage, 8m (Klon)		1.20E-02	0.00E+00	0.00E+00	1.17E-02	3.27E-04	-1.07E-03
• Bitumenemulsion (40% bitumen, 60% vand) (Klon)	0	9.93E-03	0.00E+00	0.00E+00	9.60E-03	3.27E-04	0.00E+00

• Konstruktionstræ af fyr og gran, Savede og tørrede (Forbrænding EoL) (Klon)	0	1.72E-03	0.00E+00	0.00E+00	1.72E-03	0.00E+00	-8.75E-04
• Krydsfiner, ubehandlet (Forbrænding EoL) (Klon)	0	3.72E-04	0.00E+00	0.00E+00	3.72E-04	0.00E+00	-1.96E-04
New Roof Cassettes		5.67E-01	-5.78E-01	2.08E-02	1.11E+00	9.39E-03	-5.73E-01
Loft, gipsbaserede akustikpaneler på træforskalling		1.53E-01	9.84E-03	0.00E+00	1.37E-01	6.31E-03	-6.90E-02
• Gipskartonplade 13 mm, hulplade	0	2.98E-02	2.73E-02	0.00E+00	0.00E+00	2.55E-03	0.00E+00
• Gipskartonplade 13 mm, imprægneret	0	3.55E-02	3.25E-02	0.00E+00	0.00E+00	3.00E-03	0.00E+00
• Konstruktionstræ af fyr og gran, Savede og tørrede (Forbrænding EoL)	0	8.93E-03	-1.26E-01	0.00E+00	1.35E-01	0.00E+00	-6.90E-02
• Mineraluld, alm.	0	7.87E-02	7.66E-02	0.00E+00	1.37E-03	7.59E-04	0.00E+00
Midterlag, træelement, ventileret, flade/skrå tage, 8m (Klon)		4.14E-01	-5.88E-01	2.08E-02	9.78E-01	3.08E-03	-5.04E-01
• Bitumenemulsion (40% bitumen, 60% vand)	1	3.36E-03	1.35E-03	1.68E-03	0.00E+00	3.27E-04	0.00E+00
• Dampspærre PE (tykkelse 0,0002 m)	1	3.82E-02	7.99E-03	1.91E-02	1.11E-02	0.00E+00	-1.10E-02
• Konstruktionstræ af fyr og gran, Savede og tørrede (Forbrænding EoL)	0	5.16E-02	-7.32E-01	0.00E+00	7.83E-01	0.00E+00	-3.99E-01
• Krydsfiner, ubehandlet (Forbrænding EoL)	0	3.46E-02	-1.44E-01	0.00E+00	1.78E-01	0.00E+00	-9.38E-02
• Mineraluld, alm.	0	2.86E-01	2.78E-01	0.00E+00	4.98E-03	2.76E-03	0.00E+00
Stairs		1.76E+01	8.36E-01	0.00E+00	1.68E+01	0.00E+00	-4.50E+00
Trappe i beton, per etage		2.48E+01	2.38E+01	0.00E+00	1.06E+00	0.00E+00	-2.97E-01
• Betontrappe, etagehøj	0	2.48E+01	2.38E+01	0.00E+00	1.06E+00	0.00E+00	-2.97E-01
Trappe i træ, per etage		5.18E+00	-1.11E+01	0.00E+00	1.62E+01	0.00E+00	-4.35E+00
• Lerpuds	0	1.86E+00	1.81E+00	0.00E+00	5.45E-02	0.00E+00	-7.56E-02
• Træ, fyrretræ (12% fugt / 10,7% H2O)	0	8.88E-01	-3.44E+00	0.00E+00	4.33E+00	0.00E+00	-1.14E+00
• Træ, fyrretræ (12% fugt / 10,7% H2O)	0	2.43E+00	-9.42E+00	0.00E+00	1.18E+01	0.00E+00	-3.13E+00
Terrain, pavement		6.47E-01	3.11E-01	3.23E-01	6.79E-03	5.01E-03	-9.28E-03
Belægning, betonfliser, 5 cm		6.47E-01	3.11E-01	3.23E-01	6.79E-03	5.01E-03	-9.28E-03
• Fabriksbeton C35/45 SCC	1	6.47E-01	3.11E-01	3.23E-01	6.79E-03	5.01E-03	-9.28E-03
Existing top lighting / demolition		6.96E-01	0.00E+00	0.00E+00	6.96E-01	0.00E+00	-1.84E-01
Existing frame		6.96E-01	0.00E+00	0.00E+00	6.96E-01	0.00E+00	-1.84E-01
• Beslag til dreje-kip vinduer (aluminium) (Klon)	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
• Træ, fyrretræ (12% fugt / 10,7% H2O) (Klon)	0	6.96E-01	0.00E+00	0.00E+00	6.96E-01	0.00E+00	-1.84E-01
Existing window / demolition		1.68E+00	0.00E+00	0.00E+00	1.68E+00	3.27E-03	-1.84E-01
Eksisterende Vindue, træ (Klon)		1.68E+00	0.00E+00	0.00E+00	1.68E+00	3.27E-03	-1.84E-01
• Glas 4 mm (Klon)	0	3.27E-03	0.00E+00	0.00E+00	0.00E+00	3.27E-03	0.00E+00
• Træ, fyrretræ (12% fugt / 10,7% H2O) (Klon)	0	1.68E+00	0.00E+00	0.00E+00	1.68E+00	0.00E+00	-1.84E-01
Triple Glazing		2.45E+00	1.16E+00	1.23E+00	6.07E-02	9.82E-03	-5.62E-02
R ude, 3-lags energirude		2.45E+00	1.16E+00	1.23E+00	6.07E-02	9.82E-03	-5.62E-02
• Rude, 3-lags	1	2.45E+00	1.16E+00	1.23E+00	6.07E-02	9.82E-03	-5.62E-02
Window Frame, Aluminum		2.21E+00	2.00E+00	0.00E+00	1.38E-01	6.52E-02	-1.22E+00
Karm, vinduer, aluminium		2.21E+00	2.00E+00	0.00E+00	1.38E-01	6.52E-02	-1.22E+00
• EPDM-tætning til aluminiumsprofil	0	1.97E-01	6.68E-02	0.00E+00	6.52E-02	6.52E-02	-7.05E-02
• Vinduesbeslag, aluminium	0	8.96E-02	8.96E-02	0.00E+00	0.00E+00	7.09E-06	-2.77E-02
• Vindueskarm, aluminium	0	9.45E-01	9.05E-01	0.00E+00	3.98E-02	0.00E+00	-5.46E-01
• Vinduesramme, aluminium	0	9.74E-01	9.41E-01	0.00E+00	3.25E-02	0.00E+00	-5.75E-01
Window Frame, Plastic		1.76E+00	1.14E+00	0.00E+00	5.56E-01	6.52E-02	-4.73E-01
Karm, vinduer, plast		1.76E+00	1.14E+00	0.00E+00	5.56E-01	6.52E-02	-4.73E-01

• EPDM-tætning til aluminiumsprofil	0	1.97E-01	6.68E-02	0.00E+00	6.52E-02	6.52E-02	-7.05E-02
• Vinduesbeslag, aluminium	0	8.96E-02	8.96E-02	0.00E+00	0.00E+00	7.09E-06	-2.77E-02
• Vindueskarm, plast	0	6.98E-01	4.74E-01	0.00E+00	2.25E-01	0.00E+00	-1.85E-01
• Vinduesramme, plast	0	7.76E-01	5.10E-01	0.00E+00	2.66E-01	0.00E+00	-1.89E-01
Window Frame, Wood		7.12E-01	1.27E-01	0.00E+00	5.20E-01	6.52E-02	-2.80E-01
Karm, vinduer, træ		7.12E-01	1.27E-01	0.00E+00	5.20E-01	6.52E-02	-2.80E-01
• EPDM-tætning til aluminiumsprofil	0	1.97E-01	6.68E-02	0.00E+00	6.52E-02	6.52E-02	-7.05E-02
• Vinduesbeslag, aluminium	0	8.96E-02	8.96E-02	0.00E+00	0.00E+00	7.09E-06	-2.77E-02
• Vindueskarm, træ	0	2.10E-01	-2.12E-02	0.00E+00	2.32E-01	0.00E+00	-9.31E-02
• Vinduesramme, træ	0	2.15E-01	-8.13E-03	0.00E+00	2.23E-01	0.00E+00	-8.89E-02
Window Frame, Wood-Aluminum		1.29E+00	6.82E-01	0.00E+00	5.41E-01	6.52E-02	-6.17E-01
Karm, vinduer, træ-/aluminium		1.29E+00	6.82E-01	0.00E+00	5.41E-01	6.52E-02	-6.17E-01
• EPDM-tætning til aluminiumsprofil	0	1.97E-01	6.68E-02	0.00E+00	6.52E-02	6.52E-02	-7.05E-02
• Vinduesbeslag, aluminium	0	8.96E-02	8.96E-02	0.00E+00	0.00E+00	7.09E-06	-2.77E-02
• Vindueskarm, aluminium	0	2.73E-01	2.61E-01	0.00E+00	1.15E-02	0.00E+00	-1.58E-01
• Vindueskarm, træ	0	2.10E-01	-2.12E-02	0.00E+00	2.32E-01	0.00E+00	-9.31E-02
• Vinduesramme, aluminium	0	3.04E-01	2.94E-01	0.00E+00	1.01E-02	0.00E+00	-1.79E-01
• Vinduesramme, træ	0	2.15E-01	-8.13E-03	0.00E+00	2.23E-01	0.00E+00	-8.89E-02
Existing Concrete Wall / demolition		1.34E+00	1.29E+00	0.00E+00	2.69E-02	2.00E-02	-1.13E-01
Midterdel, betonelement 200 mm		1.34E+00	1.29E+00	0.00E+00	2.69E-02	2.00E-02	-1.13E-01
• Armeringsnet	0	1.64E-01	1.64E-01	0.00E+00	0.00E+00	1.64E-04	-9.43E-02
• Fabriksbeton C30/37	0	1.17E+00	1.13E+00	0.00E+00	2.69E-02	1.99E-02	-1.84E-02
Shading, top and side lighting		1.42E+00	4.69E-01	7.10E-01	2.41E-01	0.00E+00	-4.02E-01
Solafskærmning, rulleskodder (PVC)		1.42E+00	4.69E-01	7.10E-01	2.41E-01	0.00E+00	-4.02E-01
• Rulleskodder, PVC	1	1.42E+00	4.69E-01	7.10E-01	2.41E-01	0.00E+00	-4.02E-01
Wall, Phenolic Foam		1.38E+01	1.38E+01	0.00E+00	0.00E+00	1.26E-03	-1.08E+01
• Kingspan		1.38E+01	1.38E+01	0.00E+00	0.00E+00	1.26E-03	-1.08E+01
• Aluminiumsplade	0	8.61E+00	8.61E+00	0.00E+00	0.00E+00	5.61E-04	-6.81E+00
• Aluminiumsprofil	0	5.13E+00	5.13E+00	0.00E+00	0.00E+00	3.28E-04	-3.97E+00
• Kingspan*	0	6.92E-02	6.88E-02	0.00E+00	0.00E+00	3.74E-04	0.00E+00
Wall, Wood Fiber		5.96E-01	-1.29E+00	0.00E+00	1.88E+00	0.00E+00	-9.60E-01
• Midterdel, træskelet, ikke-bærende, træfiber (Klon)		5.96E-01	-1.29E+00	0.00E+00	1.88E+00	0.00E+00	-9.60E-01
• Burnt Wood*	0	1.08E-01	-4.55E-03	0.00E+00	1.13E-01	0.00E+00	-4.25E-02
• Konstruktionstræ af fyr og gran, Savede og tørrede (Forbrænding EoL)	0	2.88E-02	-4.08E-01	0.00E+00	4.37E-01	0.00E+00	-2.23E-01
• Træfiberisolering	0	4.59E-01	-8.75E-01	0.00E+00	1.33E+00	0.00E+00	-6.94E-01

Appendix B – Results

Plot all Simulations ET

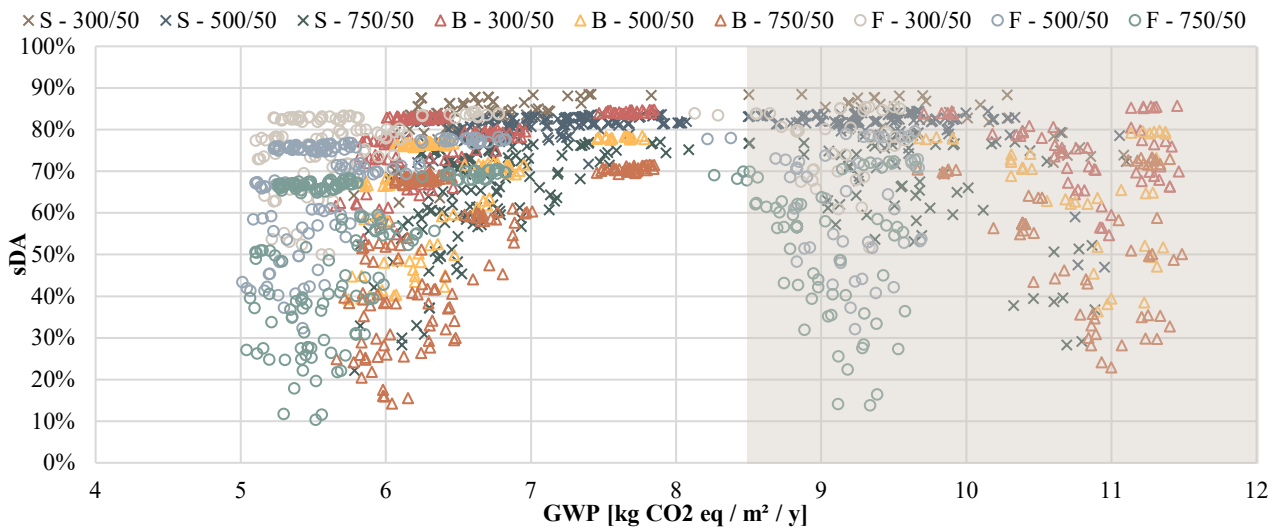


Figure 53: Scatter plot sDA (x/50%) and LCA

Scatter Plots and Result Compliance Overview BB and FB

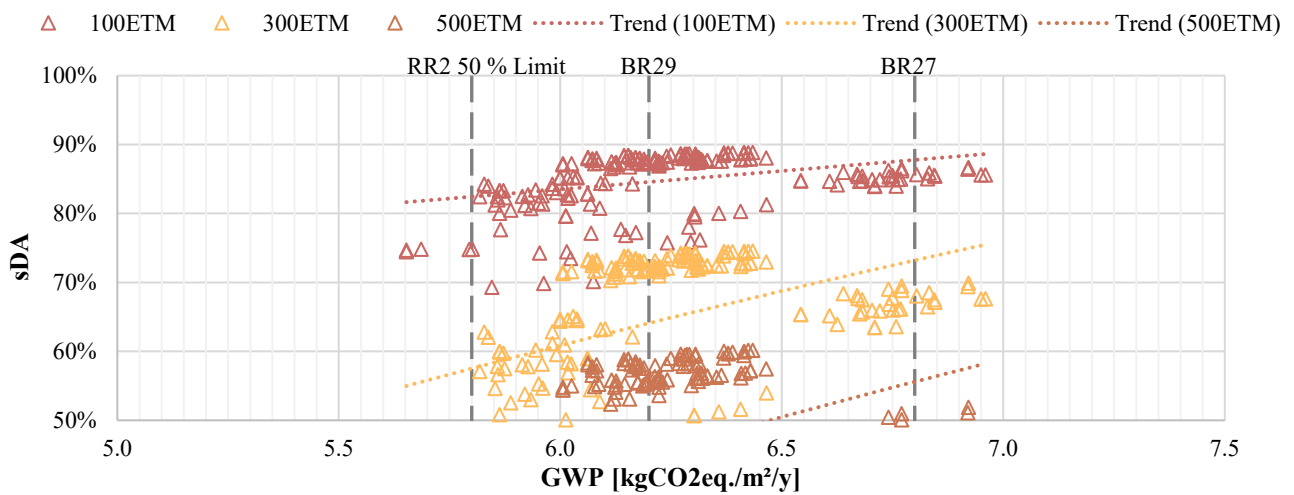


Figure 54: BB typology scatter plot, LCA and sDA (E_{TM})

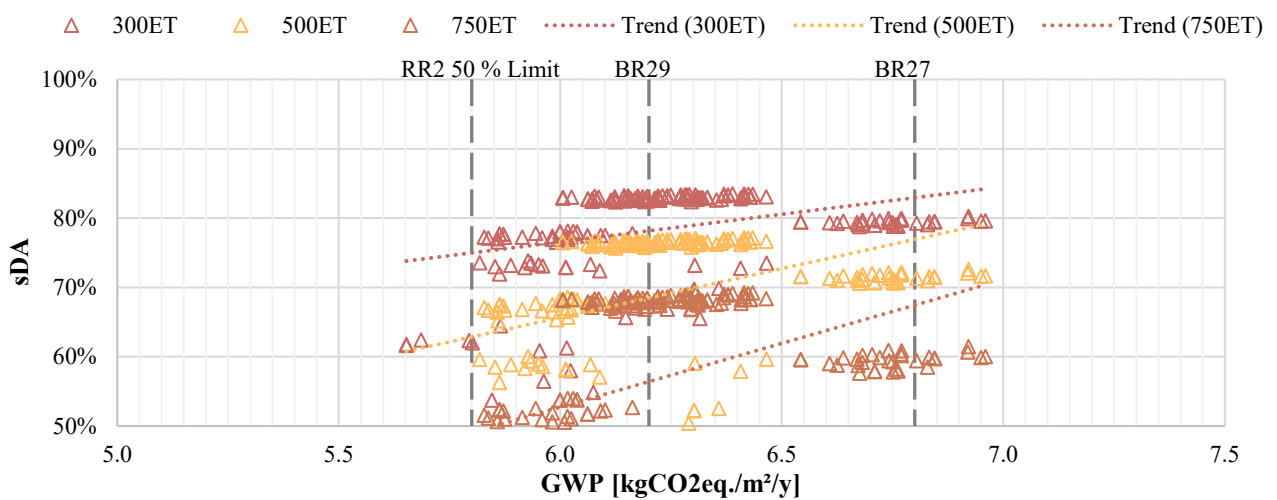


Figure 55: BB typology scatter plot, LCA and sDA (E_T)

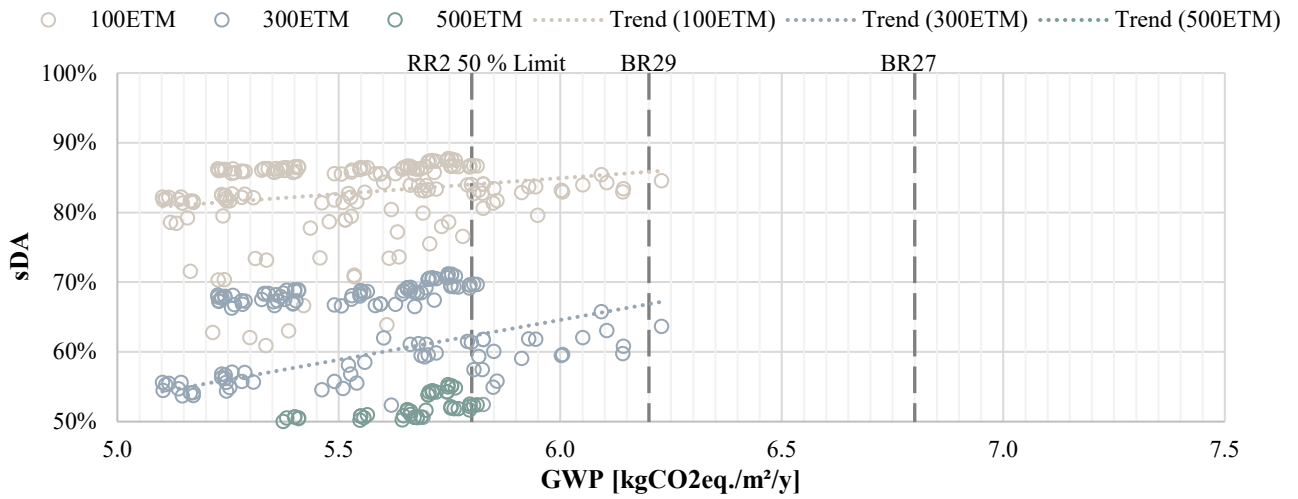


Figure 56: FB typology scatter plot, LCA and sDA (E_{TM})

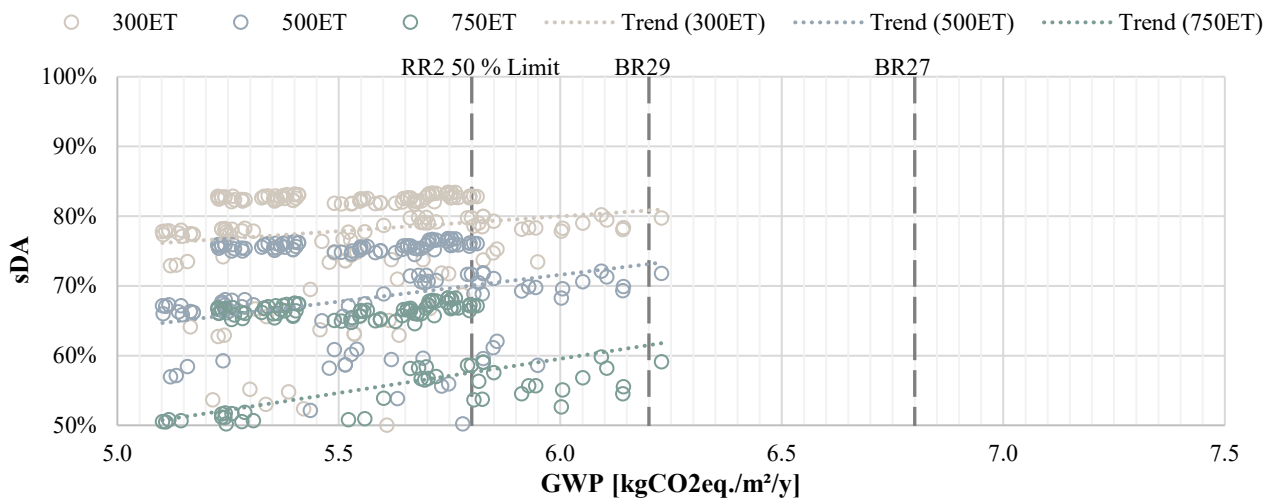
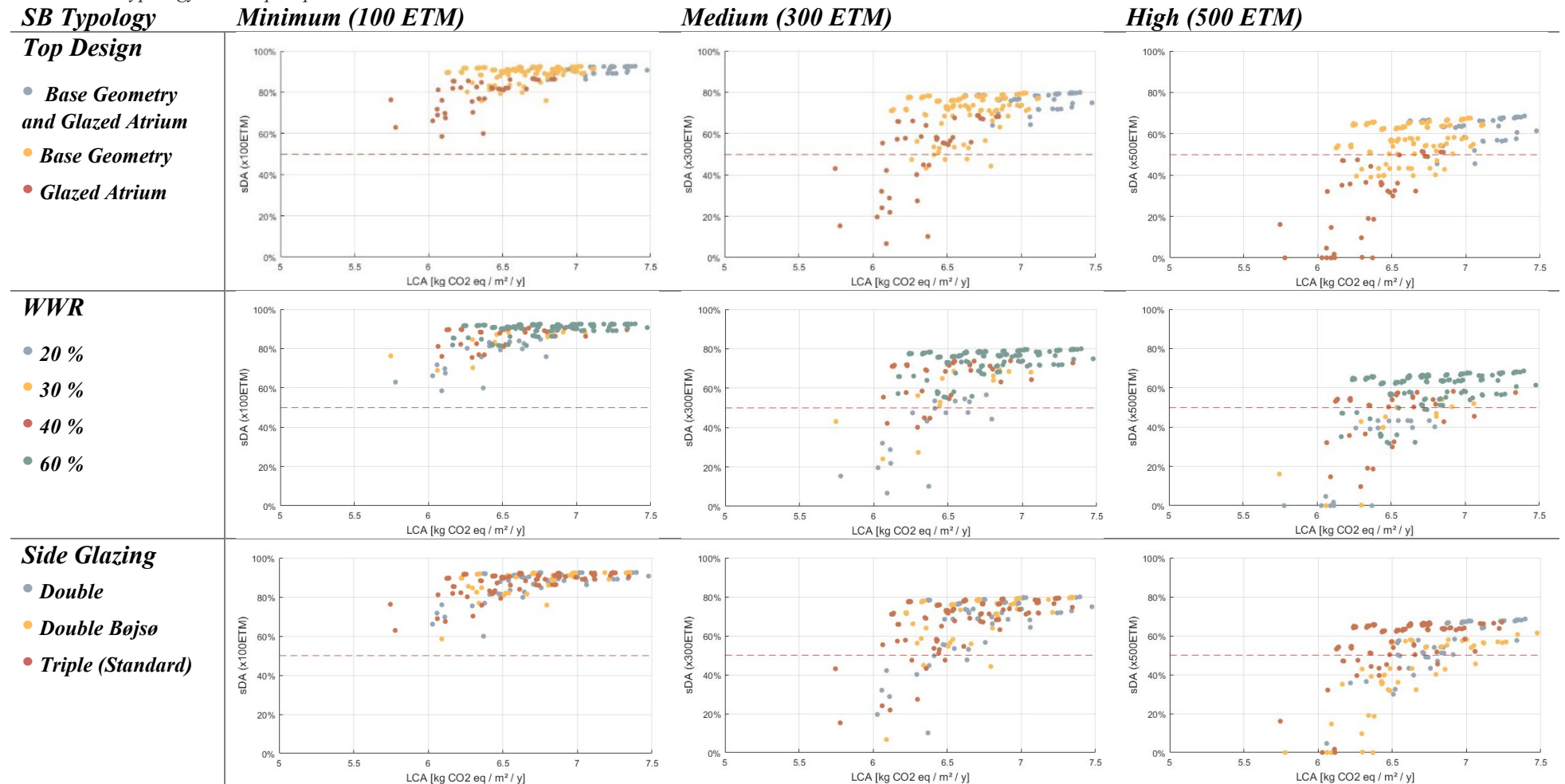


Figure 57: FB typology scatter plot, LCA and sDA (E_T)

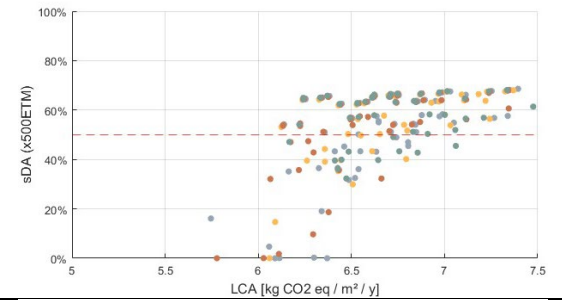
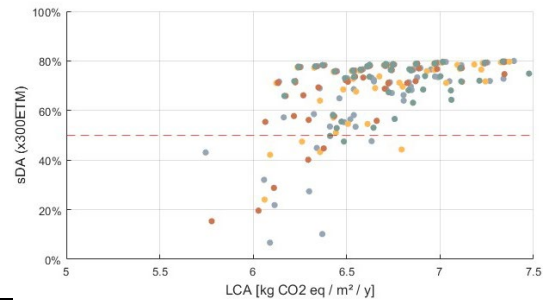
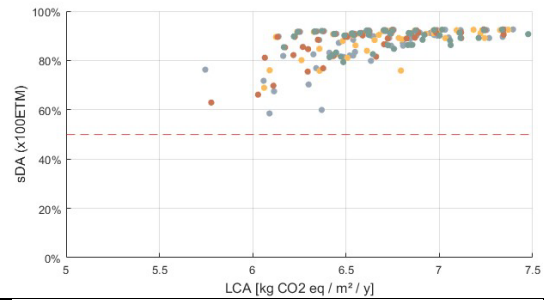
Scatter Plot Parameter Distribution

Table 39: SB typology scatter plot parameter distribution



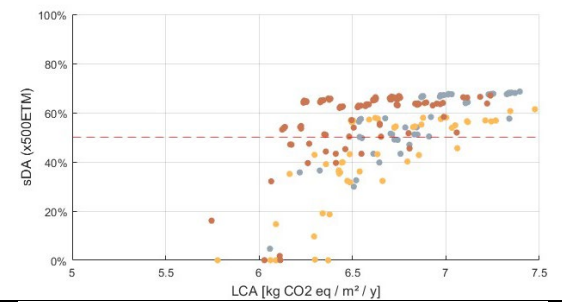
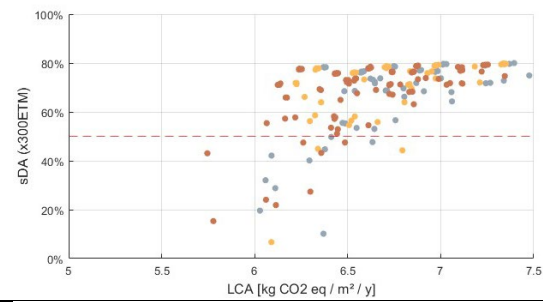
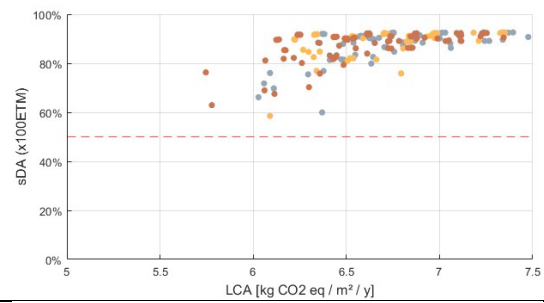
Frame

- Aluminum
- Hybrid
- PVC
- Wood



Sec. Glazing

- Double
- Double Bøjsø
- Triple (Standard)



Top Glazing

- Clear Double
- Clear Triple
- Low-E Double
- Low-E Triple

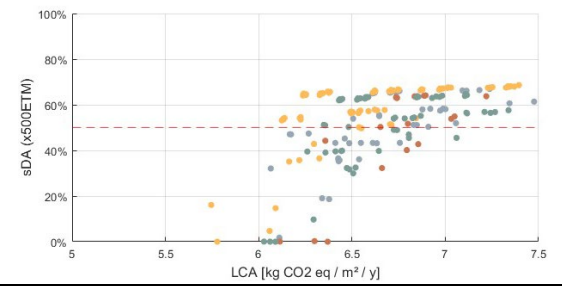
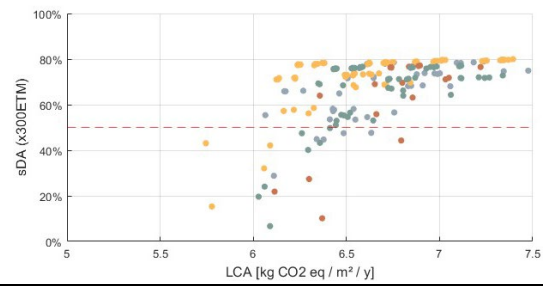
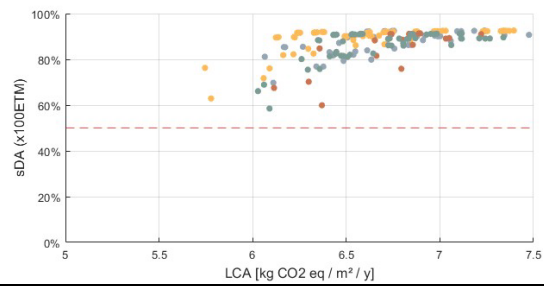
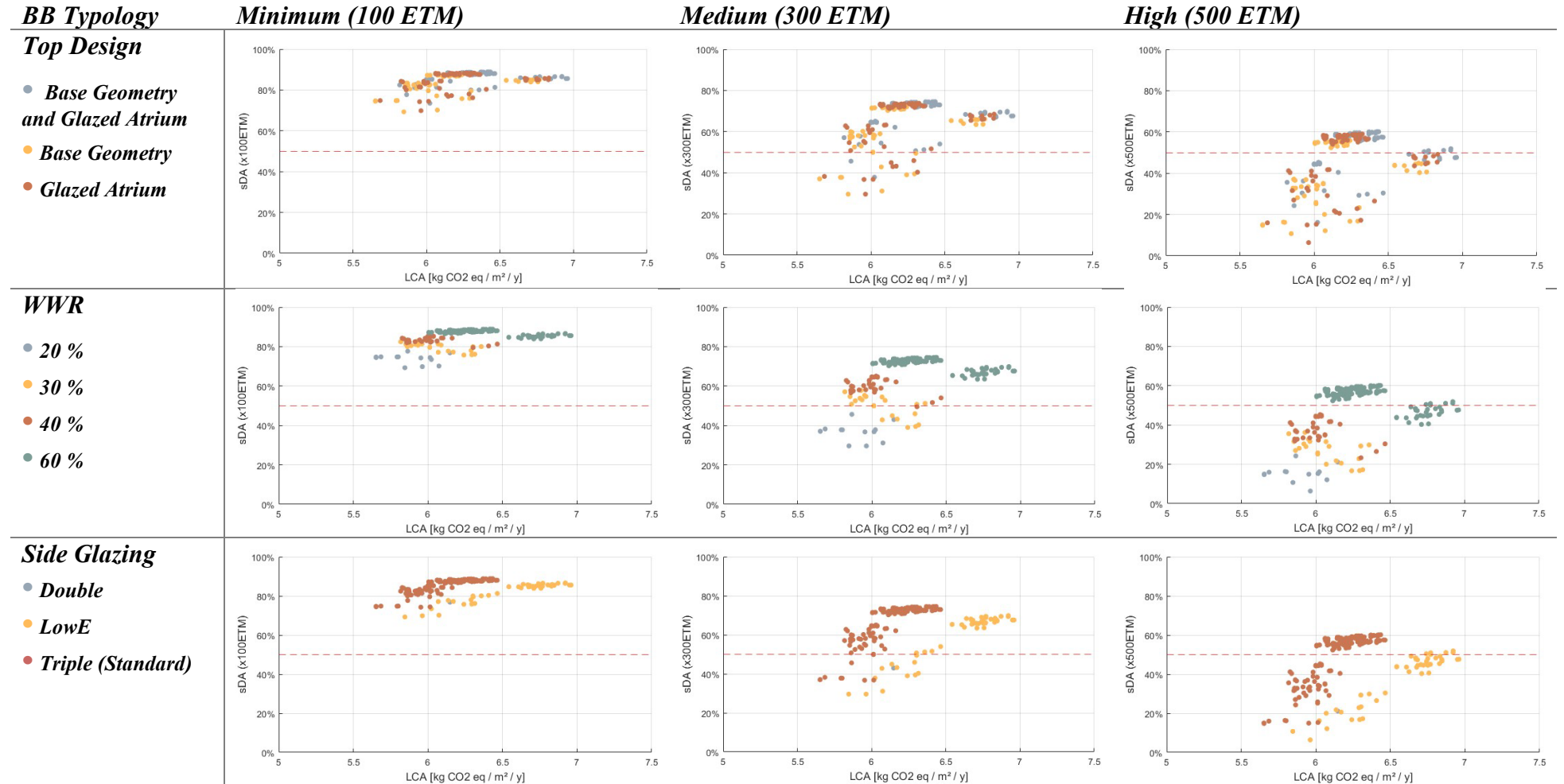
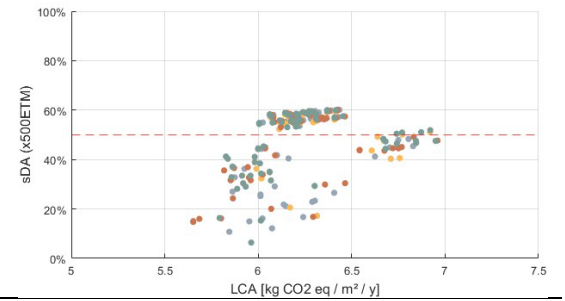
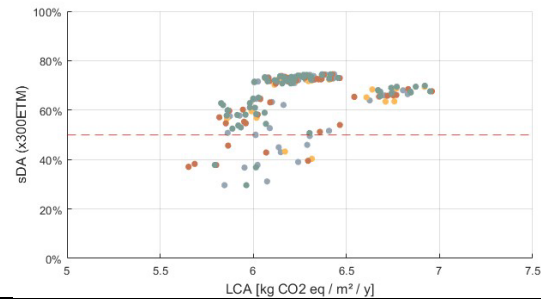
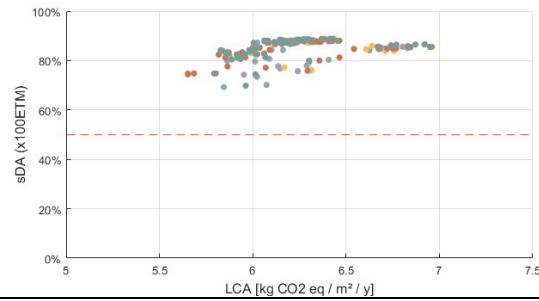


Table 40: BB typology scatter plot parameter distribution



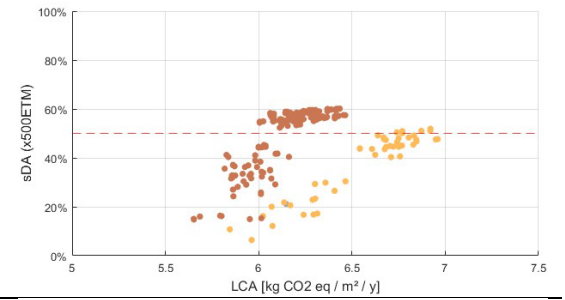
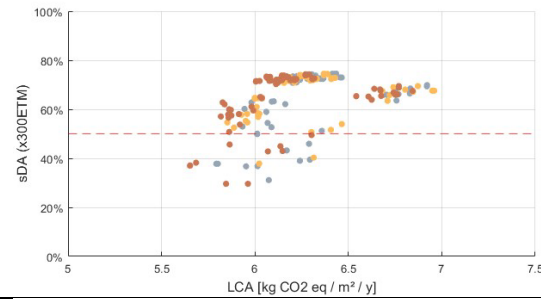
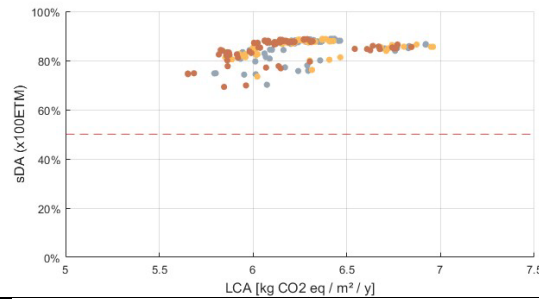
Frame

- Aluminum
- Hybrid
- PVC
- Wood



Sec. Glazing

- Double
- Double Bøjsø
- Triple (Standard)



Top Glazing

- Clear Double
- Clear Triple
- Low-E Double
- Low-E Triple

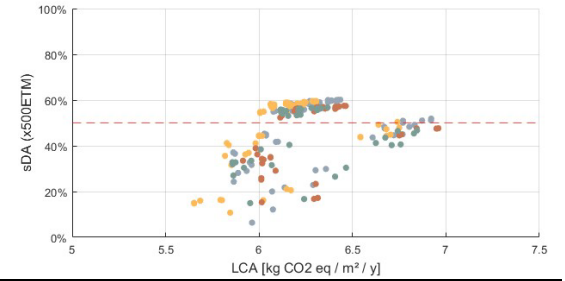
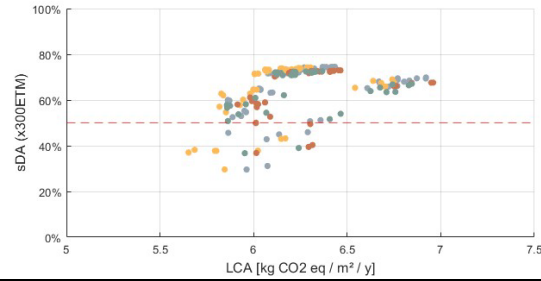
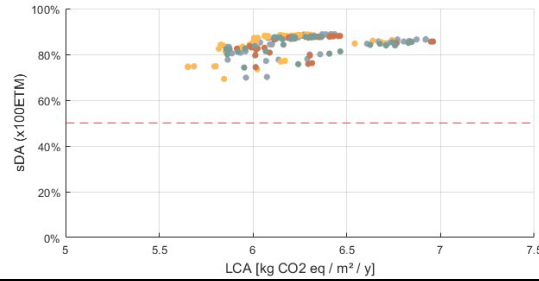
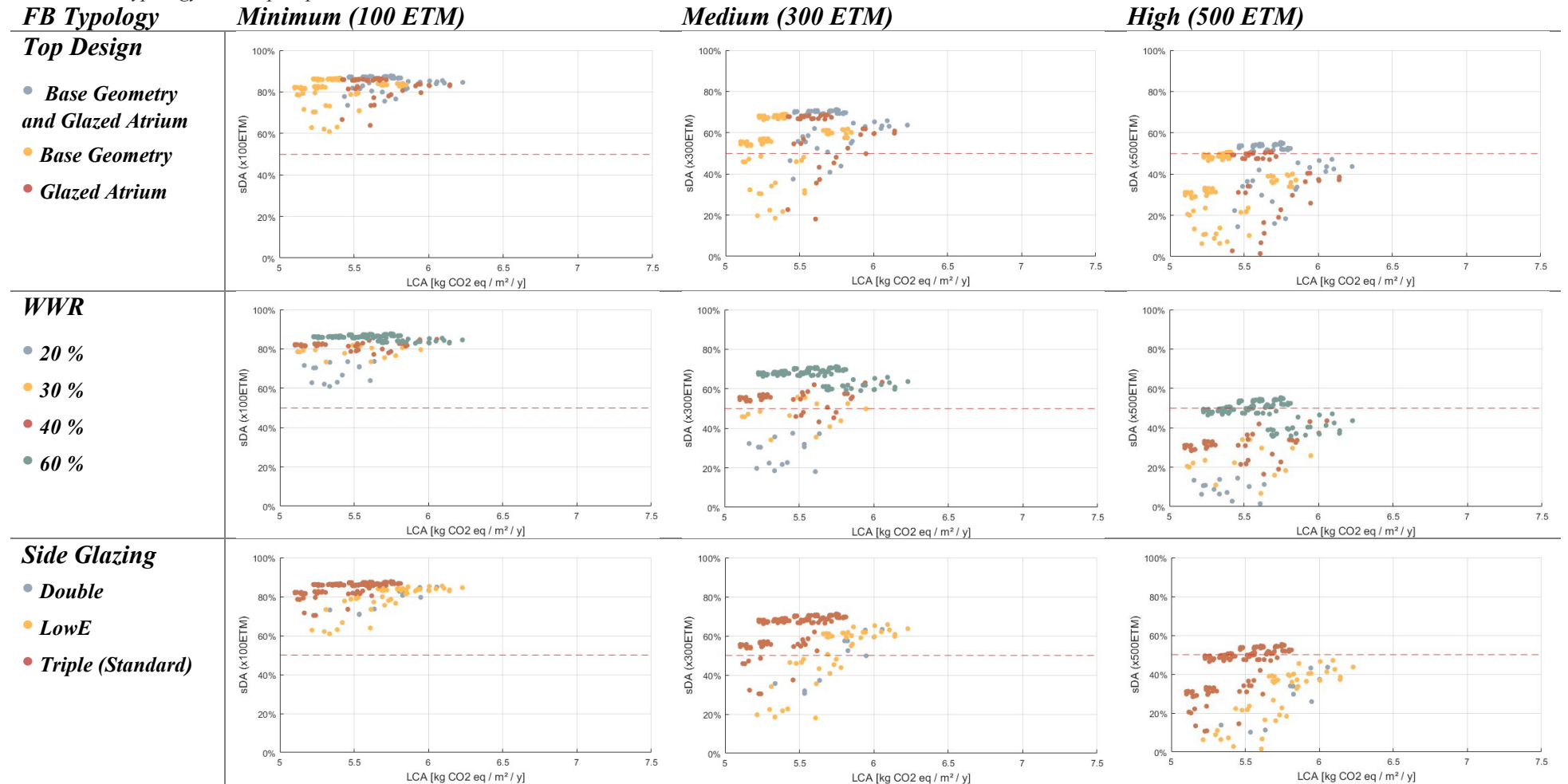
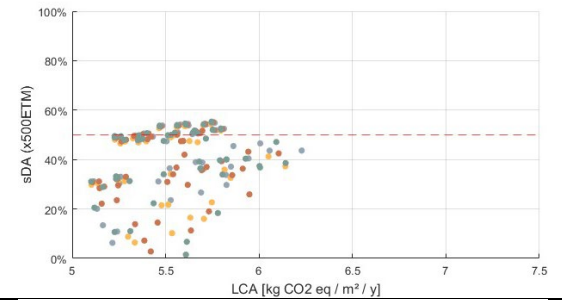
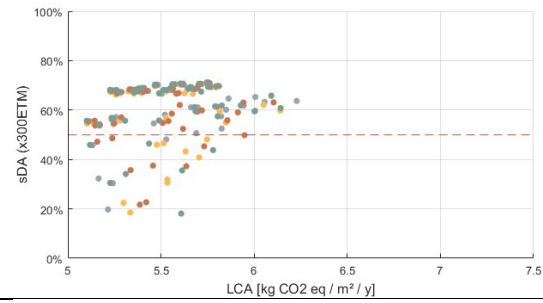
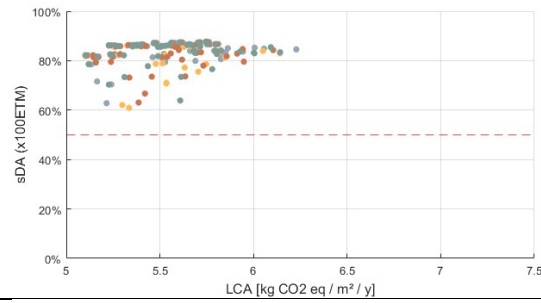


Table 41: FB typology scatter plot parameter distribution



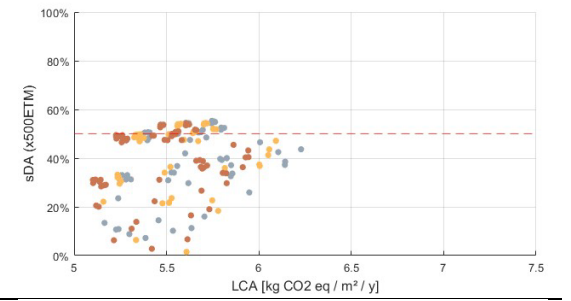
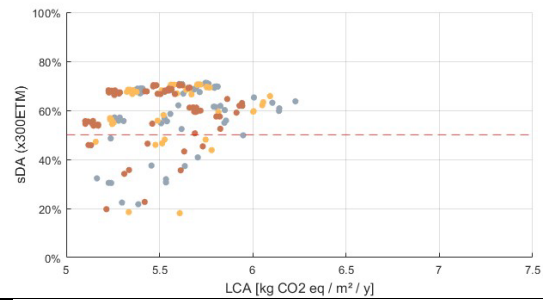
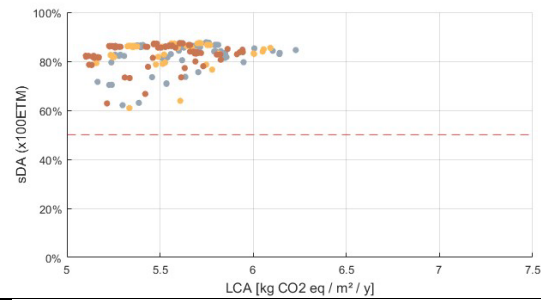
Frame

- Aluminum
- Hybrid
- PVC
- Wood



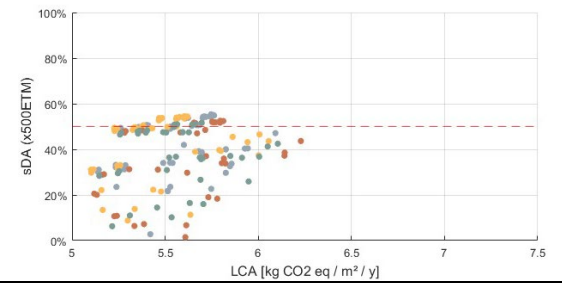
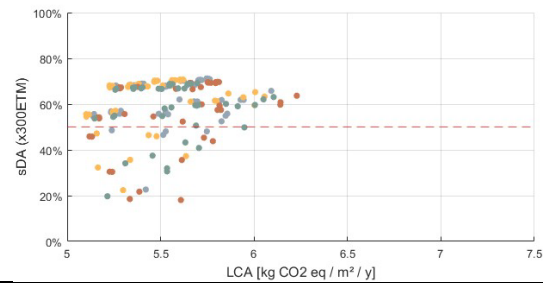
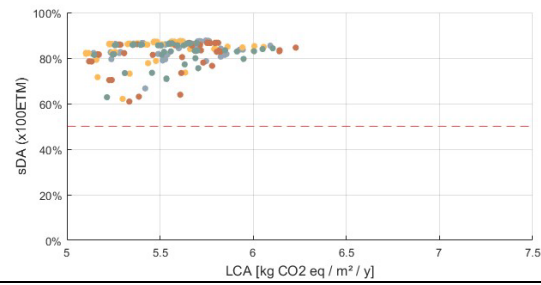
Sec. Glazing

- Double
- Double Bøjsø
- Triple (Standard)



Top Glazing

- Clear Double
- Clear Triple
- Low-E Double
- Low-E Triple



Top 5 Design Combinations by FT (LCA 100 %, sDA 0 %)

Table 42: Sawtooth Roof (SB) typology top 5 designs (100 % LCA)

LVL	TD	WWR	SGI	Frame	SecGl	TGI	LCA	x300ET	x500ET	x750ET	x100ETM	x300ETM	x500ETM	ET score	ETM score	LCA score	Composite Score
MIN	{AG}	0.3	{SStd}	{Alu}	{SecStd}	{TCTrp}	5.7456	0.76325	0.6437	0.47055	0.7628	0.4308	0.16105	0.53396	0.52288	1	1
	{AG}	0.2	{LowE}	{PVC}	{SecStd}	{TCTrp}	5.7778	0.64145	0.4298	0.2152	0.6292	0.1533	0	0.063875	0.12965	0.97979	0.97979
	{AG}	0.2	{SStd}	{PVC}	{SecDbf}	{TSTrp}	6.0284	0.68595	0.4919	0.28825	0.6613	0.19615	0.00055	0.23562	0.22414	0.82254	0.82254
	{AG}	0.2	{SDBf}	{Alu}	{SecDbf}	{TCTrp}	6.0582	0.7202	0.5525	0.3764	0.7176	0.32045	0.04695	0.36781	0.38985	0.80384	0.80384
MED	{AG}	0.3	{LowE}	{Hyb}	{SecStd}	{TSTrp}	6.0608	0.7019	0.51885	0.31235	0.6893	0.24045	0.0001	0.29718	0.30655	0.80221	0.80221
	{FT}	0.4	{SStd}	{PVC}	{SecStd}	{TCTrp}	6.1332	0.8546	0.7797	0.6784	0.89545	0.71095	0.5387	0.87765	0.88249	0.75678	0.75678
	{AG}	0.4	{SDBf}	{PVC}	{SecStd}	{TCTrp}	6.2178	0.80525	0.721	0.5961	0.8219	0.5775	0.3572	0.74019	0.6996	0.70369	0.70369
	{FT}	0.6	{SStd}	{Hyb}	{SecStd}	{TCTrp}	6.2376	0.8749	0.8201	0.74305	0.9161	0.7744	0.64315	0.97225	0.96944	0.69127	0.69127
	{FT}	0.6	{SStd}	{Wood}	{SecStd}	{TCTrp}	6.2416	0.87635	0.8215	0.74485	0.9168	0.77715	0.6493	0.97553	0.97321	0.68876	0.68876
HIGH	{FT}	0.6	{SStd}	{PVC}	{SecStd}	{TCTrp}	6.2464	0.8758	0.8203	0.7437	0.9167	0.77625	0.64715	0.97272	0.97197	0.68574	0.68574
	{FT}	0.4	{SStd}	{Hyb}	{SecStd}	{TCTrp}	6.1238	0.8532	0.778	0.6725	0.89545	0.71065	0.5316	0.84092	0.78581	0.76268	0.76268
	{FT}	0.4	{SStd}	{PVC}	{SecStd}	{TCTrp}	6.1332	0.8547	0.78045	0.6792	0.89545	0.71085	0.5363	0.85234	0.79276	0.75678	0.75678
	{FT}	0.4	{SStd}	{Alu}	{SecStd}	{TCTrp}	6.1382	0.8546	0.78125	0.6784	0.89705	0.71635	0.5421	0.85098	0.80133	0.75364	0.75364
	{FT}	0.4	{SStd}	{PVC}	{SecDbfB}	{TCTrp}	6.2248	0.85505	0.78375	0.6823	0.89775	0.7187	0.5459	0.85763	0.80695	0.6993	0.6993
	{FT}	0.6	{SStd}	{Hyb}	{SecStd}	{TCTrp}	6.2376	0.87465	0.81975	0.74155	0.91625	0.7752	0.64335	0.95865	0.951	0.69127	0.69127

Table 43: Barrel Roof (BB) typology top 5 designs (100 % LCA)

LVL	TD	WWR	SGI	Frame	SecGl	TGI	LCA	x300ET	x500ET	x750ET	x100ETM	x300ETM	x500ETM	ET score	ETM score	LCA score	Composite Score
MIN	{FT}	0.2	{SStd}	{PVC}	{SecStd}	{TCTrp}	5.6524	0.61633	0.40935	0.24405	0.74687	0.37093	0.15052	0.26538	0.27671	1	1
	{AG}	0.2	{SStd}	{PVC}	{SecStd}	{TCTrp}	5.685	0.62415	0.42247	0.264	0.74815	0.38225	0.1599	0.29173	0.28323	0.97505	0.97505
	{FT}	0.2	{SStd}	{Wood}	{SecDbf}	{TCTrp}	5.7934	0.6233	0.42335	0.26053	0.74757	0.37793	0.16345	0.28886	0.28029	0.8921	0.8921
	{FT}	0.2	{SStd}	{PVC}	{SecDbf}	{TCTrp}	5.8012	0.62003	0.42002	0.25735	0.7481	0.37775	0.16205	0.27784	0.28298	0.88613	0.88613
	{FT+AG}	0.3	{SStd}	{PVC}	{SecStd}	{TCTrp}	5.8176	0.7355	0.59578	0.42037	0.8245	0.57073	0.35587	0.66661	0.67357	0.87358	0.87358
MED	{AG}	0.4	{SStd}	{Wood}	{SecStd}	{TCTrp}	5.8274	0.77217	0.67083	0.5158	0.84262	0.6281	0.4121	0.76694	0.73905	0.86609	0.86609
	{AG}	0.3	{SStd}	{PVC}	{SecDbfB}	{TCTrp}	5.8524	0.72995	0.5851	0.4028	0.81222	0.5464	0.3161	0.56854	0.55714	0.84695	0.84695
	{FT}	0.4	{SStd}	{Wood}	{SecStd}	{TSTrp}	5.857	0.77028	0.66438	0.50662	0.82417	0.5781	0.32825	0.75201	0.62772	0.84343	0.84343
	{FT}	0.4	{SStd}	{Wood}	{SecStd}	{TCDbl}	5.8624	0.77705	0.67512	0.52397	0.83337	0.59908	0.36978	0.77689	0.67442	0.8393	0.8393
	{FT}	0.4	{SStd}	{Alu}	{SecStd}	{TSTrp}	5.8742	0.77233	0.66725	0.50995	0.82317	0.57495	0.32785	0.75866	0.62071	0.83027	0.83027
HIGH	{AG}	0.6	{SStd}	{Wood}	{SecStd}	{TCTrp}	6.0618	0.82785	0.7637	0.67917	0.88065	0.73325	0.58252	0.97594	0.96501	0.68672	0.68672
	{AG}	0.6	{SStd}	{Hyb}	{SecStd}	{TCTrp}	6.0644	0.8251	0.7599	0.6725	0.87787	0.72825	0.57283	0.96341	0.94696	0.68473	0.68473
	{AG}	0.6	{SStd}	{PVC}	{SecStd}	{TCTrp}	6.0722	0.8273	0.76318	0.67817	0.87995	0.7314	0.58052	0.97406	0.96129	0.67876	0.67876
	{FT}	0.6	{SStd}	{Hyb}	{SecStd}	{TSDbl}	6.1132	0.82517	0.75843	0.6697	0.86498	0.70288	0.52353	0.95816	0.85521	0.64738	0.64738
	{AG}	0.6	{SStd}	{Hyb}	{SecStd}	{TSTrp}	6.118	0.82225	0.75645	0.6666	0.87197	0.71527	0.54685	0.95235	0.89862	0.64371	0.64371

Table 44: Flat Roof (FB) typology top 5 designs (100 % LCA)

LVL	TD	WWR	SGI	Frame	SecGI	TGI	LCA	x300ET	x500ET	x750ET	x100ETM	x300ETM	x500ETM	ET score	ETM score	LCA score	Composite Score
MIN	{FT}	0.4	{SStd}	{Hyb}	{SecStd}	{TCTrp}	5.1029	0.77327	0.65987	0.48897	0.8184	0.54503	0.2977	0.81799	0.78041	0.99893	0.99893
	{FT}	0.3	{SStd}	{Wood}	{SecStd}	{TSDbl}	5.1193	0.72873	0.56957	0.3783	0.78583	0.45877	0.2054	0.6846	0.659	0.98438	0.98438
	{FT}	0.3	{SStd}	{Alu}	{SecStd}	{TSDbl}	5.1327	0.7297	0.5711	0.37953	0.78477	0.45777	0.2006	0.6875	0.65503	0.97248	0.97248
	{FT}	0.4	{SStd}	{PVC}	{SecStd}	{TCDbl}	5.1435	0.7796	0.6713	0.50633	0.82213	0.55667	0.3111	0.83696	0.79433	0.9629	0.9629
	{FT}	0.3	{SStd}	{PVC}	{SecDbIB}	{TCTrp}	5.1581	0.73467	0.58427	0.39187	0.7923	0.4717	0.22123	0.70238	0.68311	0.94994	0.94994
MED	{FT}	0.4	{SStd}	{Wood}	{SecStd}	{TCTrp}	5.1017	0.778	0.67147	0.50527	0.8224	0.55623	0.31073	0.80103	0.70627	1	1
	{FT}	0.4	{SStd}	{PVC}	{SecStd}	{TCTrp}	5.1087	0.77837	0.6703	0.5047	0.8204	0.55337	0.30837	0.79862	0.70088	0.99379	0.99379
	{FT}	0.4	{SStd}	{Alu}	{SecStd}	{TCTrp}	5.1157	0.77887	0.673	0.50777	0.82187	0.5549	0.31187	0.8042	0.70376	0.98757	0.98757
	{FT}	0.4	{SStd}	{Hyb}	{SecStd}	{TCDbl}	5.1377	0.77557	0.66287	0.49243	0.8185	0.54707	0.303	0.78328	0.68902	0.96805	0.96805
	{FT}	0.4	{SStd}	{PVC}	{SecStd}	{TSTrp}	5.1465	0.77113	0.6585	0.48623	0.8137	0.53737	0.28393	0.77426	0.67077	0.96023	0.96023
HIGH	{FT}	0.6	{SStd}	{Wood}	{SecDbIB}	{TCDbl}	5.4001	0.8316	0.76387	0.67503	0.8656	0.68973	0.5067	0.98696	0.91339	0.73513	0.73513
	{FT+AG}	0.6	{SStd}	{Hyb}	{SecStd}	{TSTrp}	5.5473	0.82203	0.7516	0.6566	0.8627	0.68323	0.5023	0.95492	0.90522	0.60447	0.60447
	{AG}	0.6	{SStd}	{Alu}	{SecDbIB}	{TCDbl}	5.6427	0.82037	0.75207	0.65723	0.86207	0.68333	0.5026	0.95602	0.90578	0.51979	0.51979
	{FT+AG}	0.6	{SStd}	{Wood}	{SecStd}	{TSDbl}	5.6547	0.8255	0.7572	0.66643	0.8656	0.692	0.5163	0.97201	0.93122	0.50914	0.50914
	{FT+AG}	0.6	{SStd}	{PVC}	{SecStd}	{TSDbl}	5.6617	0.8251	0.75617	0.6644	0.8662	0.69283	0.5153	0.96848	0.92936	0.50293	0.50293

LCA Top Solutions

Table 45: LCA all building elements top solutions SB

	<i>Fixed</i>	<i>Operative</i>	<i>Roof</i>	<i>Demolition</i>	<i>SL Sec Glazing</i>	<i>Facade</i>	<i>SL Glazing</i>	<i>SL Frames</i>	<i>TL Glazing</i>	<i>TL Frames</i>	<i>TL Shading</i>	<i>SL Shading</i>	<i>Total</i>	<i>% increase</i>
SB HIGH	1.72E+00	2.62E+00	2.68E-01	7.29E-02	4.57E-02	1.40E-01	1.11E-01	3.29E-03	7.14E-01	1.44E-02	3.02E-01	1.16E-01	6.12E+00	-0.15%
SB MED	1.72E+00	2.62E+00	2.68E-01	7.29E-02	4.57E-02	1.40E-01	1.11E-01	4.51E-03	7.14E-01	1.91E-02	3.02E-01	1.16E-01	6.13E+00	6.53%
SB MIN	1.72E+00	2.56E+00	2.27E-01	5.47E-02	4.57E-02	2.23E-01	8.33E-02	5.64E-03	5.13E-01	2.32E-04	2.17E-01	9.67E-02	5.75E+00	

Table 46: LCA all building elements top solutions BB

	<i>Fixed</i>	<i>Operative</i>	<i>Roof</i>	<i>Demolition</i>	<i>SL Sec Glazing</i>	<i>Facade</i>	<i>SL Glazing</i>	<i>SL Frames</i>	<i>TL Glazing</i>	<i>TL Frames</i>	<i>TL Shading</i>	<i>SL Shading</i>	<i>Total</i>	<i>% increase</i>
BB HIGH	1.65E+00	2.95E+00	1.42E-01	2.22E-01	4.78E-02	2.09E-01	3.38E-01	2.23E-03	1.59E-01	2.42E-04	6.72E-02	2.76E-01	6.06E+00	3.94%
BB MED	1.65E+00	2.99E+00	1.42E-01	0.137633825	0.04783981	2.35E-01	2.10E-01	2.23E-03	1.59E-01	2.42E-04	6.72E-02	1.86E-01	5.83E+00	3.05%
BB MIN	1.65E+00	3.09E+00	1.48E-01	6.88E-02	4.78E-02	2.51E-01	1.05E-01	5.52E-03	1.20E-01	2.95E-03	5.09E-02	1.13E-01	5.65E+00	

Table 47: LCA all building elements top solutions FB

	<i>Fixed</i>	<i>Operative</i>	<i>Roof</i>	<i>Demolition</i>	<i>SL Sec Glazing</i>	<i>Facade</i>	<i>SL Glazing</i>	<i>SL Frames</i>	<i>TL Glazing</i>	<i>TL Frames</i>	<i>TL Shading</i>	<i>SL Shading</i>	<i>Total</i>	<i>% increase</i>
FB HIGH	1.49E+00	2.80E+00	2.03E-01	1.63E-01	4.60E-02	1.65E-01	2.48E-01	2.05E-03	5.48E-02	1.63E-03	2.32E-02	2.12E-01	5.400993	5.70%
FB MED	1.49E+00	2.70E+00	2.03E-01	1.02E-01	4.71E-02	1.83E-01	1.55E-01	2.05E-03	5.48E-02	1.63E-03	2.32E-02	1.48E-01	5.10E+00	-0.02%
FB MIN	1.49E+00	2.70E+00	2.03E-01	1.02E-01	4.71E-02	1.83E-01	1.55E-01	3.72E-03	5.48E-02	1.14E-03	2.32E-02	1.48E-01	5.10E+00	

Table 48: Percentual impact per building element (minimum threshold)

<i>Normalized</i>	<i>Fixed</i>	<i>Operative</i>	<i>Roof</i>	<i>Demolition</i>	<i>SL Sec Glazing</i>	<i>Facade</i>	<i>SL Glazing</i>	<i>SL Frames</i>	<i>TL Glazing</i>	<i>TL Frames</i>	<i>TL Shading</i>	<i>SL Shading</i>
SB MIN	29.76%	44.47%	3.94%	0.95%	0.79%	3.87%	1.44%	0.10%	8.89%	0.36%	3.76%	1.68%
BB MIN	29.17%	54.66%	2.62%	1.22%	0.85%	4.44%	1.85%	0.10%	2.13%	0.05%	0.90%	2.01%
FB MIN	30.34%	55.01%	2.08%	0.96%	3.74%	3.16%	0.08%	1.12%	0.02%	0.47%	3.02%	0.00%

Table 49: Envelope percentual impact

	<i>Opaque Envelope</i>	<i>Top Lighting</i>	<i>Side Lighting</i>	<i>Total Fenestration</i>
SB MIN	8%	9%	6%	15.58%
BB MIN	7%	3%	6%	9.10%
FB MIN	8%	2%	8%	9.26%

Minimum, Medium, and High Threshold Box Plots by FT and Floor

Flat Roof (FB) Formal Typology

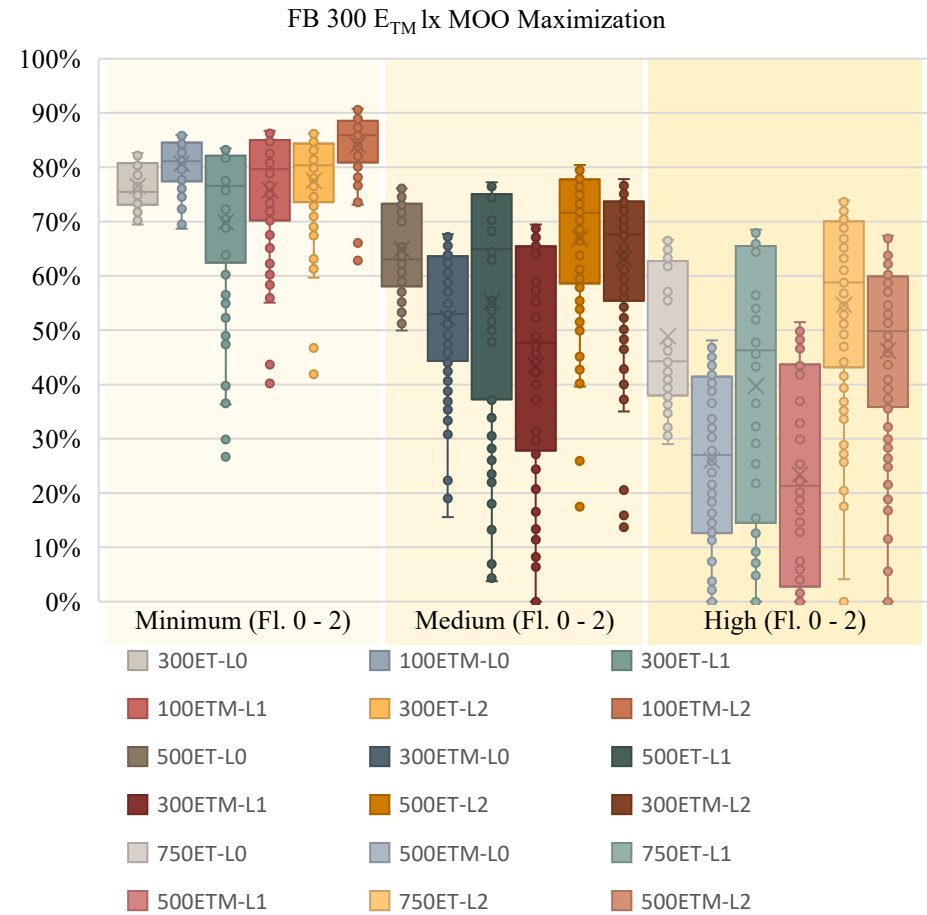
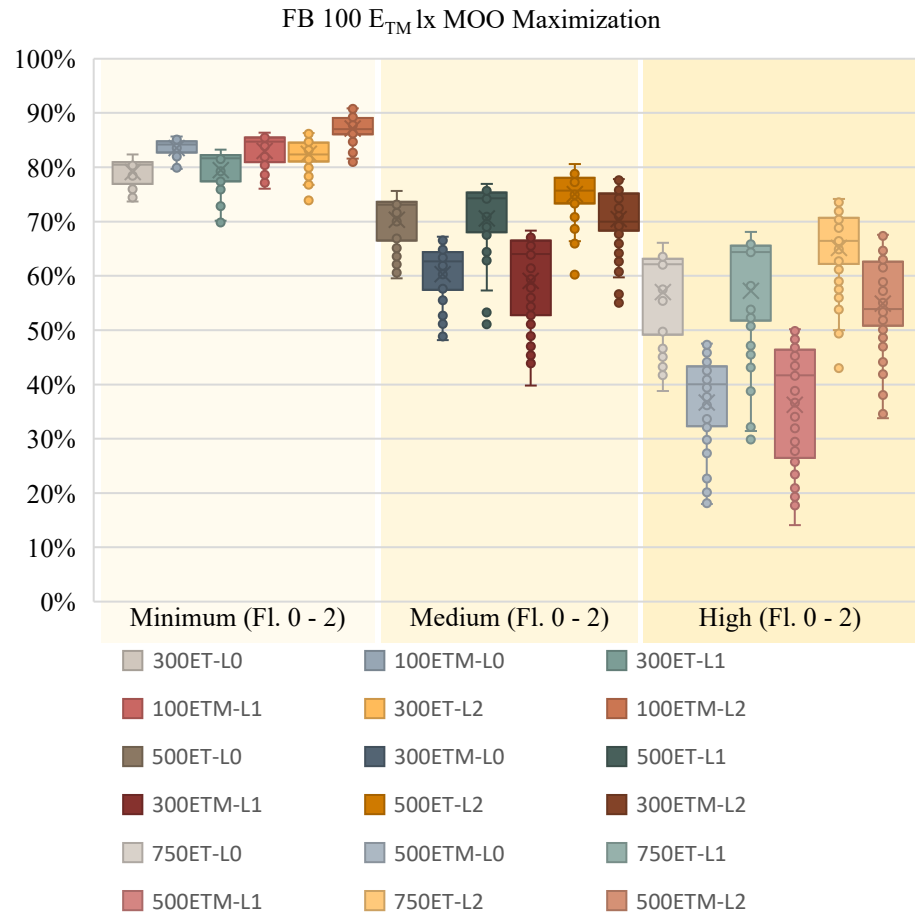


Figure 58: Box plot visualizations of the MOO maximization results for the 100 E_{TM} lx and 300 E_{TM} lx optimization, with data filtered and grouped by floor for the FB formal typology

Barrel Roof (BB) Formal Typology

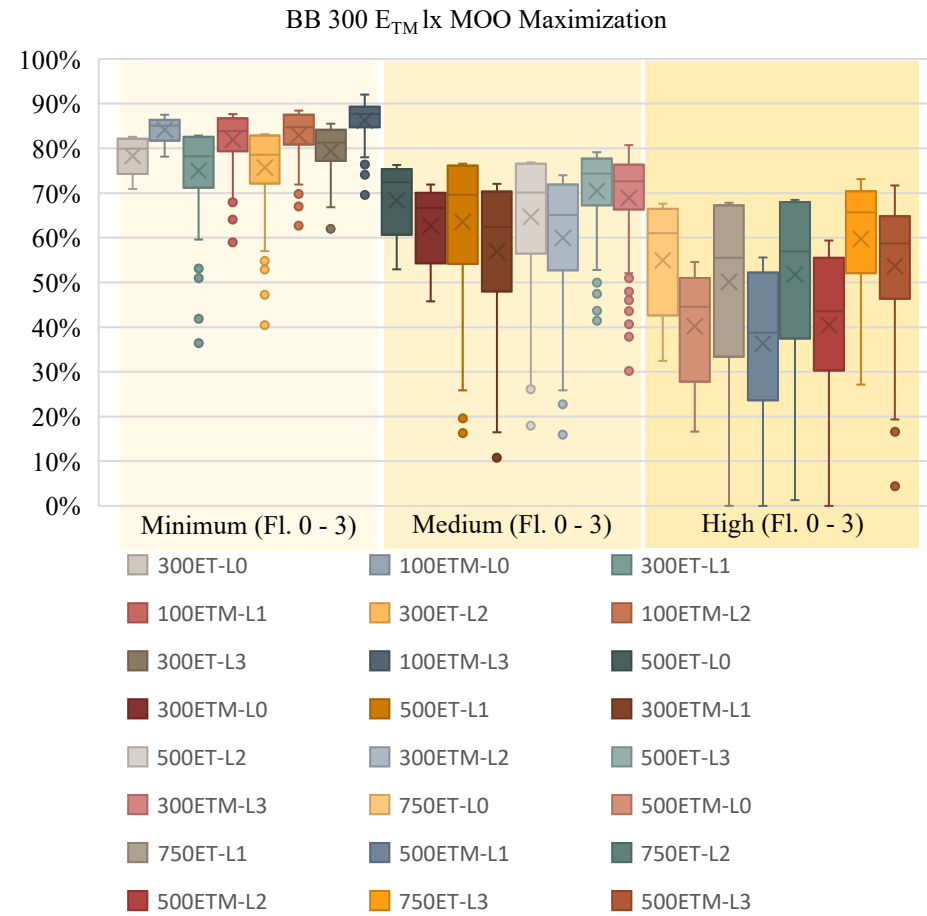
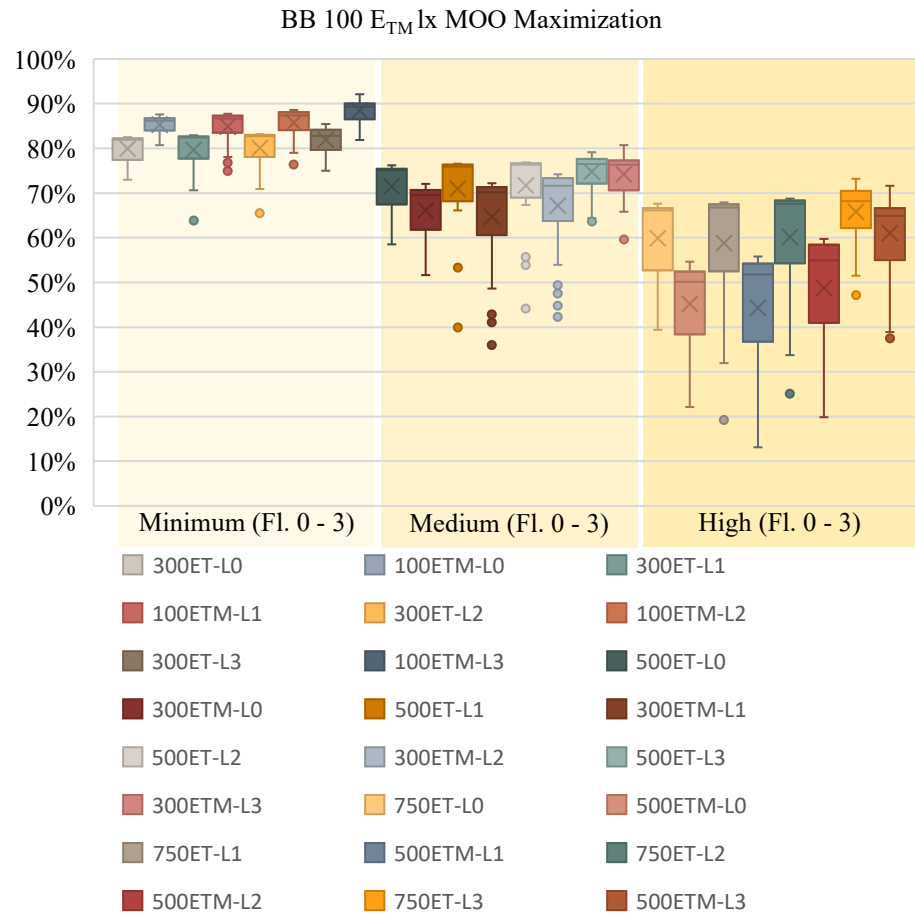


Figure 59: Box plot visualizations of the MOO maximization results for the 100 E_{TM} lx and 300 E_{TM} lx optimization, with data filtered and grouped by floor for the BB formal typology

Sawtooth Roof (SB) Formal Typology

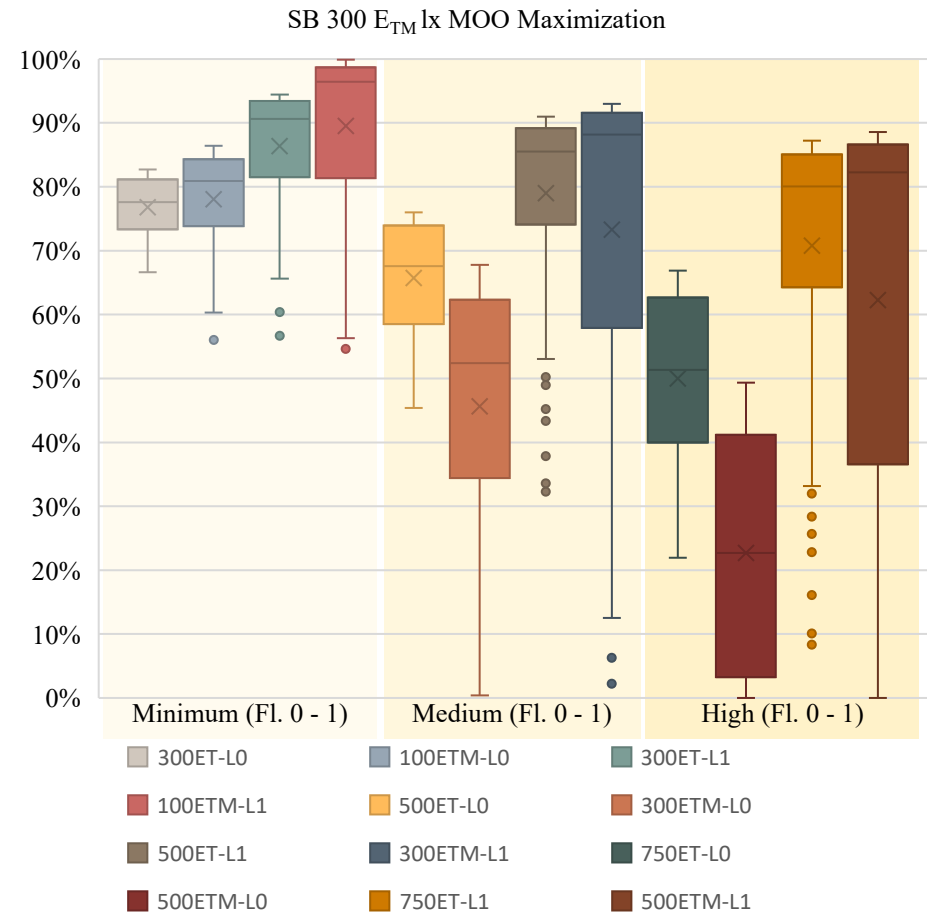
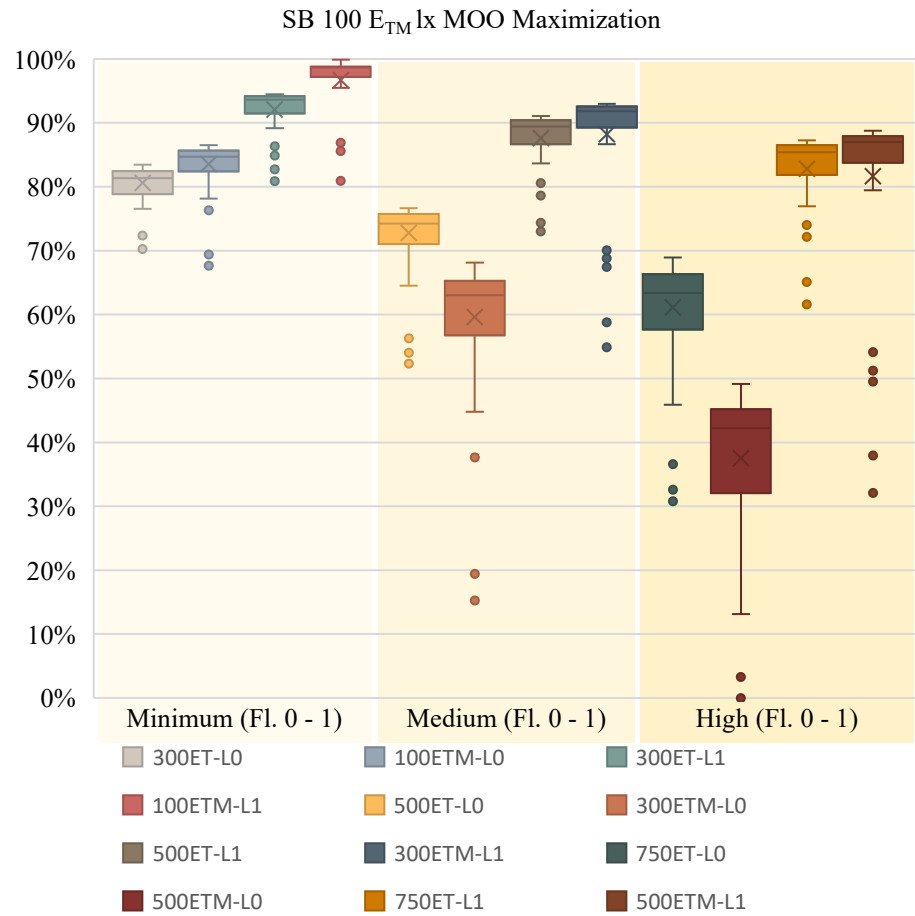


Figure 60: Box plot visualizations of the MOO maximization results for the 100 E_{TM} lx and 300 E_{TM} lx optimization, with data filtered and grouped by floor for the SB formal typology

Appendix C – Use of GAI

I used GAI tools in my report: **YES**

- Grammarly, Google Translate, Microsoft 365 Editor, ChatGPT, Gemini, and Connected Papers were used in this thesis. The tools were used in the following ways listed below.

I used a GAI tool as language editor: **YES**

- Grammarly and Microsoft 365 Editor for finding and correcting grammar errors like spelling and punctuation.

I used GAI to retrieve information: **YES**

- Connected papers and ChatGPT deep search. Helped find sources to then read over and quality check to see if the source was valid or useful literature to contribute to the study.

I used GAI to get help with writing code: **YES**

- Engaged in iterative back-and-forth sessions with Gemini and ChatGPT models to develop MATLAB code for filtering large excel datasets.

I used GAI for translations: **YES**

- ChatGPT and Google Translate were used to help translate English searches to Finnish, Icelandic, Swedish, and Norwegian. Specifically, when searching through building law texts.

I used GAI to generate graphs/images: **NO**

I used GAI to help structure my content: **YES**

- Grammarly and Microsoft Editor helped with recommendations for the placement of sections and paragraphs, however, all text was written by the authors. The structure was quality checked to ensure alignment with Lund University academic writing standards on *LUP Student Papers*, *Lund University Libraries*.

Note: The authors have understood, and quality checked all generated code and any other content which was developed with the help of GAI tools. The authors have explained in the methodology and this appendix all GAI content present in the report.

The structuring of this appendix is based on the GAI policy posted on the 8th of March 2024 titled, “*Policy for Generative Artificial Intelligence at the master’s programme in Energy-efficient and Environmental Building Design.*”



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