A LIFE-CYCLE APPROACH METHODOLOGY TO EVALUATE INTEGRATED DAYLIGHTING SOLUTIONS

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Master thesis in Energy-efficient and Environmental Buildings
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Lund University

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

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

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Keywords:	daylighting system, daylighting assessment, life-cycle assessment (LCA), LCA methodology, Global Warming Potential (GWP)
Publication year:	2024

Abstract

The objective of this work was to develop a harmonised Life-Cycle Assessment methodology tailored specifically for assessing the environmental impact of daylighting systems. These systems include various architectural features, such as windows, skylights, or shading devices, designed to optimize the use of daylight in a space. This project aligns with the efforts to unify LCA practices within the construction field, while fostering a more comprehensive approach to the building environmental assessment.

The research process was conducted in two steps. Initially, an extensive literature review was performed, including five prevalent methodologies currently employed in LCA for buildings. The goal of this phase was to gain a deep understanding of their core features and identify their applicability to daylighting systems. Subsequently, the second step culminated with de development of a harmonised methodology based on LCA principles, adhering to the structure established in the standards ISO 14040 and 14044:2006. This approach employs a cradle-to-grave approach, encompassing three pivotal performance aspects of daylight systems: daylight quality, energy performance, and environmental impact. This holistic approach provides a deeper insight of the system's overall impact, while considering the quality of selected solution.

In the proposed methodology, the results are expressed in terms of the Global Warming Potential (GWP), quantified as CO_2-eq per kWh of primary energy consumption difference, compared to a baseline system over a 50-year period. The baseline system reflects the average window in the European building stock. Additionally, a minimum daylight factor median (DFm) of 1% is required for both the baseline and the novel system. To illustrate its application, the harmonised methodology is then applied considering the adoption of a hypothetical electrochromic glazing assembly for a building retrofit in two different spatial contexts, representing a closed and an open office plan, based on the standardized PASSYS and BESTEST test cells.

The research process resulted in several lessons learned. Firstly, by including a minimum daylight performance threshold, it underscored the importance of adopting a holistic approach to environmental, energy performance, and daylighting quality. Secondly, the study highlighted the importance of context-based evaluations, point out to the importance of variable such as building design, maintenance practices, climatic conditions, or energy sources. Lastly, establishing a baseline emerged as a critical aspect for creating accurate and meaningful comparative assessments, clearly distinguishing between well-performing and poorly performing systems.

Acknowledgement

I would like to start by thanking my supervisor and co-supervisor, Niko Gentile, and Víctor Ferreira. I know this project presented challenges, I was not always the easiest student to supervise, but I deeply appreciate your continuous help, patience, and support.

Thanks, as well to my examiner, Jouri Kanters, for your understanding and insightful questions comments. They have made me reflect upon my work and have undoubtedly improved the outcome.

I would also like to express my gratitude to my colleagues at BIG. Having the chance to work alongside so many passionate and knowledgeable people has been a true gift. It is impossible to quantify how much of this work is thanks to your guidance and collaboration.

To my friends at Östra and everyone I met during this programme at Lund. Thanks for all your help and the fun times. I will always cherish these memories with you.

Of course, my deepest thanks go to my parents and my brother. I am forever grateful for all the effort and sacrifice you have made over the years to help me. Thanks for your unwavering support. You have always put my happiness first, and that meant the world. I hope you are proud of me; I certainly am proud of you. *Moitas grazas!*

Lastly, to my partner, Maja. There are not enough words to express my gratitude. You have been my rock throughout this whole journey. Thanks for being by my side, for your help, your support, understanding and for always pushing me to achieve my best. None of this could have been possible without you. *Kocham cię!*

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Abbreviations

ADF	Average Daylight Factor
ASE	Annual Sunlight Exposure
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers.
CI	Carbon Intensity
COP	Coefficient of Performance
DA	Daylight Autonomy
DF	Daylight Factor
DFm	Daylight Factor Median
DFp	Point Daylight Factor
EPD	Environmental Product Declaration
EUI	Energy Use Intensity
FU	Functional Unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEED	Leadership in Energy and Environmental Design
ReqSL	Required Service Life
RSP	Reference Study Period
sDA	Spatial Daylight Autonomy
TMY	Typical Meteorological Year
UDI	Useful Daylight Illuminance

1 Introduction

The construction sector is responsible for about 40% of the global primary energy consumption (Levermore, 2008) and accounts for approximately 23% of the total CO_2 emissions coming from economic activities (Huang et al., 2018). Moreover, it generates approximately 50% of all the inert waste in the world (Santolini et al., 2023). These reasons make the construction sector a key target for sustainable development efforts.

As the push for sustainability acquires momentum, the need to create buildings that are environmentally friendly and occupant-focused is increasing (Cedeño-Laurent et al., 2018). Reconciling these two goals can be challenging, as strategies that improve indoor comfort may sometimes lead to compromises in energy performance, and vice versa (Pérez-Lombard et al., 2008; Shaikh et al., 2014). However, the construction industry is responding to this challenge by embracing sustainable design and construction practices, which has led to a greater demand for buildings that are both energy efficient and provide high levels of comfort (Shaikh et al., 2014).

Significant progress has been made in designing performant buildings concerning energy use and comfort. However, much has still to be understood on how we should build to reduce the environmental impact of buildings during the entire life cycle. Therefore, it is imperative to develop a holistic approach that considers both energy and environmental performance, as well as indoor comfort and well-being, throughout the whole life cycle of buildings. This is where Life-Cycle Assessment (LCA) has become key in research and practice (Dos Santos Gervasio & Dimova, 2018).

Today's highly energy-efficient daylighting systems, as well as advances in lighting design, play a significant role in reducing the need for electric lighting during daylight hours without necessarily causing heating or cooling concerns. These systems, including strategically positioned windows, skylights, shading systems and other architectural features, can save up to 75% of the energy used for lighting buildings and reduce air conditioning costs (Dubois & Blomsterberg, 2011). This minimizes energy consumption during the use phase of buildings; however, advanced daylighting and lighting systems may be more resource intensive during their production and disposal phases, consequently having higher overall environmental impact than traditional systems. Research has proved that the current energy requirements increase the "embodied" greenhouse gas (GHG) emissions by up to 50% (Röck et al., 2020). This is why the evaluation of the environmental sustainability of daylighting systems needs to be performed under a holistic perspective, being the LCA methodology the most recognised tool to such end.

LCA methodology allows assessing the environmental impact of a product or service over its entire lifecycle. By elaborating an LCA, the environmental impacts associated with a building, or specific systems, can be quantified and the most significant areas – commonly referred to as "hot spots" – can be identified and used as the starting point for improving the environmental performance. The standards ISO 14040:2006 (International Organization for Standardization, 2006a) and 14044:2006 (International Organization for Standardization, 2006b) provide guidelines to follow when performing an LCA. However, several limitations must be considered. Uncertainty exists because of the extensive data required to account for all material and energy flows associated with the systems under study, particularly concerning the life cycle phases that are located either at the top or bottom of the supply chain (Finnveden et al., 2009; Röck et al., 2018). Moreover, because extremely complicated and frequently globalized value chains are studied, it is frequently required to make assumptions about processes for which data are not accessible, or it is required to utilize average data in terms of spatial and temporal resolution (e.g., national, annual) (Finnveden et al., 2009).

Research on building LCA includes studies with different boundary conditions, inputs to consider, ways of computing emissions, energy use, etc. The same considerations apply to current normative frameworks. For example, the European standard EN 15978:2011 (European Committee for Standardization, 2011) codifies LCA for buildings. The whole building LCA process is provided by ISO 21931 (International Organization for Standardization, 2022), which states standard references and modelling assumptions. The ASTM Standard E2921 (ASTM, 2022) further describes how to compare whole buildings' LCAs in codes, standards, and rating systems. More focused on the American market, the American Institute of Architects published the AIA Guide to Building Life Cycle Assessment in Practice and the Carbon Leadership Forum published the document Life Cycle Assessment of Buildings: A Practice Guide, in 2010 and 2019 respectively (Bayer et al., 2010; Carbon Leadership Forum, 2019). And these are just part of the overwhelming body of standards and guidelines published in recent years, resulting in significant variations in results and increasing the difficulty of comparing the environmental impact of different buildings.

To improve consistency and reliability in LCA results, it is crucial to continue the search for common methodologies, with the final goal of achieving standardized approaches. With harmonised procedures, architects and engineers can make more informed decisions regarding the sustainability of building projects.

Given this context, this project aims to contributing to the standardisation of LCA practices, focusing specifically on the use of daylight in buildings. By highlighting the importance of this factor and providing standardized methods for its evaluation, this project aims to make it easier for industry professionals to incorporate sustainable practices into their building designs.

1.1 Research Questions

- What is the performance of daylighting systems concerning the baseline assessed by a harmonised approach based on multiple methodologies?
- How can be decided if a case study is environmentally preferable to a baseline?
- How does the variation of certain processing variables influence the overall environmental impacts of a daylighting system with specific features?

1.2 Objectives

In order to improve standardisation in the field of building-integrated daylighting systems, this study aims to conduct an environmental impact assessment from a life cycle perspective, based on the LCA methodology and taking into account methodological aspects of existing guidelines and standards. To propose this new harmonised methodology, an extensive literature review of current methodologies is conducted. The objective is to create a methodology that describes the environmental performance of novel daylighting solutions, addressing minimum requirements for lighting quality compared to a conventional solution. The term “daylight systems” includes any strategy or technology aimed at optimizing the use of daylight for interior illumination, including elements such as windows, skylights or shading devices.

To evaluate the proposed methodology’s performance and suitability to evaluating daylight systems, both conventional and novel solutions are applied to two standardized study case rooms: PASSYS and BESTEST Case 600, representing a single-occupant office and an open-plan office, respectively. By conducting the environmental impact assessment of both solutions, this study seeks to contribute to a better understanding of the environmental benefits of building-integrated daylighting systems.

1.3 Limitations

The application of the harmonised methodology in this study encountered limitations due to project constraints, including data availability and timeframes. In order to ensure feasibility, the application of the harmonised methodology was limited to the manufacturing and use life-cycle stages, covering the modules A1-A3, B4 and B6. Additionally, the scenarios considered that the energy consumption of the study rooms is covered exclusively by a fully electric building system.

This approach omitted potential environmental impacts from periodic maintenance and repairs (modules B2 and B3) as well as the performance decay over time. Additionally, no uncertainty or sensitivity were performed.

1.4 Disposition

This report presents a proposed methodology for LCA with a focus on daylighting considerations. The first section is an introduction describing the topic, presenting the research questions, and outlining the motivation for the study. The following section, named state-of-the-art, presents the current situation in the field, regarding daylight in buildings and LCA. There is an extensive literature review about LCA to summarize and compare some of the most important and commonly used methodologies, leading to the proposal of a new harmonised methodology with a focus on daylighting considerations in the third part. The fourth section focuses on the application of this methodology to a study case. Finally, the report is closed by the discussions and conclusions derived from the development and application of the harmonised methodology, in sections five and six, respectively.

2 State-of-the-art

2.1 Daylight

Daylight plays an important role in promoting sustainable building design, improving the occupants' health and well-being, while reducing the energy consumption. Extensive research has established that exposure to natural light impacts human mental states and physiological responses (Dubois et al., 2019). Additionally, optimal levels of natural illumination decrease the reliance on electric lighting, resulting in reduced GHG emissions and internal heat loads (Li & Lam, 2001).

Considering these goals, it is crucial to use appropriate daylighting techniques to optimise the provision of natural light in buildings. This access should be a careful assessment adapted to the local climate, more than placing windows or skylights at random. In addition, modern day devices can be installed to enhance this provision, including light shelves, solar tubes, and transparent interior partitions.

Equally important is to control the excessive penetration of light, so the inclusion of shading devices is essential in the design process. Besides traditional shading systems, the implementation of dynamic shading systems, incorporating technologies like electrochromic glazing and automated blinds, has had an impact in daylight management. These systems can react to the incident light, adapting to optimize the daylight availability and solar gains, or reducing overheating and glare (Elzeyadi, 2017). The synergy between these dynamic shading systems and indoor sensors has led to a reduction in energy consumption because of reduced use of electric lighting (Dubois & Blomsterberg, 2011) and the enhancement of occupant comfort (Dong et al., 2019).

To ensure sufficient natural light in buildings, several building regulations have established minimum requirements, based on different daylight measuring metrics that assess the quantity and quality of the daylight in a space. Traditionally, Daylight Factor (DF) has been used as a guideline for this purpose. DF is the ratio of indoor to outdoor horizontal illumination under overcast sky conditions. However, DF has certain limitations that make it limited for evaluating daylight provision. It is a static metric and does not take into consideration aspects such as local climate, façade orientation, and occupancy patterns (Müeller, 2013). Hence, there is a need to explore new dynamic and comprehensive metrics for evaluating natural light in buildings.

In response to these limitations, daylighting regulations are shifting towards dynamic daylight metrics that incorporate Climate-Based Daylight Modelling (CBDM), considering the weather data for a whole year. Some of the most common metrics in requirements and guidelines are Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), and Annual Daylight Glare probability (DGP) among others (Dubois et al., 2019).

The European countries have varying requirements for daylight provision of buildings based on different approaches. In some countries, such as France, a minimum window area based on the size and function of the daylit space is established (Ministère de la Transition Écologique, 2020). Others, like Denmark, set minimum horizontal illuminance levels and require consideration of outdoor views (Bolig- og Planstyrelsen, 2023).

With the goal of unifying these criteria, a new European standard has emerged. In 2018, the first European standard focused exclusively on daylight design was released, the EN 17037. This document divides the daylight quantification into four different aspects: daylight provision, setting target indoor illuminance levels horizontally; access to sunlight, establishing minimum hours of direct sunlight; prevention of glare, ensuring that spaces open to daylight do not suffer from excessive glare; and assessment of the view out, accounting for factors such as distance of the background or number of visible layers (European Committee for Standardization, 2018).

Lastly, many voluntary environmental certifications address the aspect of the daylight quality in their requirements, such as LEED, BREEAM, or the Swedish Miljöbyggnad. However, several establish still the DF as their metric to evaluate the quality of daylight instead of using dynamic daylight metrics (Vangeloglou & Rasmussen, 2015).

In conclusion, the use of natural light in building design has both environmental and human health benefits, making it an essential consideration in sustainable building design. Regulations and certifications are rapidly evolving, incorporating and strengthening the requirement for daylight quality in indoor spaces. Additionally, dynamic daylight metrics are becoming the basis of these requirements and their incorporation into building standards can help ensure the creation of healthy, sustainable environments.

2.2 Life-Cycle Assessment (LCA)

LCA is an environmental management technique, as defined by ISO 14040 as "the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (International Organization for Standardization, 2006a). It is a commonly used tool to evaluate the environmental performance of a product or service during its entire lifetime and consequently support the decision-making process.

The concept of LCA began to be developed in the 60s, focusing initially on reducing the energy need and the reduction of environmental emissions in the packaging industry (Bjørn et al., 2017). An increase in the popularity of this method leads to the need for standardisation, a process that was started in 1993 by the ISO Technical Committee (Pryshlakivsky & Searcy, 2013). This process resulted in the publication of standards ISO 14040 to 14043 between 1997 and 2000, providing procedures and methods for conducting LCA. In 2006, the standards were revised and consolidated into ISO 14040 and 14044, which continue today as the most widely recognized guidelines for conducting LCA.

Regarding the building industry, the life-cycle approach was mentioned for the first time in the early 80s, with a study focused on the use of renewable resources (Bekker, 1982). After the standardisation process in the 1990s, the popularity of the LCA method began to grow rapidly in the early 21st century, becoming a largely studied field in the last decade (Anand & Amor, 2017).

Currently, the incorporation of LCA into the construction process has become an essential element, with numerous legislative institutions including it in their policies. For example, Denmark has introduced limits on CO_2 emissions for new buildings larger than 1 000 m² (Nordic Sustainable Construction, 2023), while Sweden mandates the submission of a climate declaration for new buildings to obtain a building permit (Boverket, 2021). Additionally, similar to the previous section, widely used environmental certification schemes include, to a greater or lesser extent, certain credits assigned to LCA (Boverket, 2019).

Despite the significant benefits of LCA as a decision-support tool, its widespread adoption is limited by certain factors. Uncertainty and lack of data, variations in the initial inputs considered, and the flexibility in the process lead to results that are often incomparable and a consequent lack of trust (Chau et al., 2015) besides the time and monetary cost (One Click LCA, 2020).

In conclusion, LCA has already become a crucial tool for the evaluation of environmental impacts, supporting informed decision-making, rapidly growing in importance despite the substantial challenges, being the absence of standardisation one of the most pressing (Mathieux et al., 2020). Ultimately, the success of LCA in addressing environmental issues and promoting sustainability depends on its ability to overcome these challenges and provide reliable data for future decision-making.

2.2.1 Study and comparison of current LCA methodologies

Figure 1 includes a general representation of different LCA standards and regulations in the construction sector, presenting them in a tiered structure depending on their level of detail. The generic frameworks are placed at the top providing foundational principles, while more specific standards and certifications are at the bottom, offering detailed guidance for particular aspects of LCA.

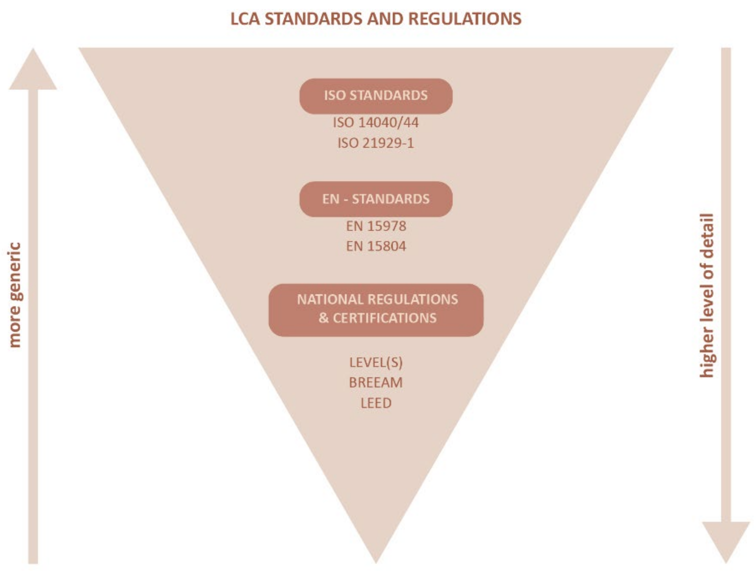

Figure 1: Key LCA standards and regulations in the construction sector and their level of detail.

This section provides a summary of several methodologies, each of which is relevant to the topic under investigation, concluding with a comprehensive table summarising the main highlights and differences found during the review. By providing a clear and organized summary of the most important and widely used methodologies, this section will help to acquire a deeper understanding of the current state-of-the-art in the field and lay the groundwork for the proposal of a new harmonised methodology in subsequent sections.

ISO 14040 - Environmental management – Life cycle assessment –Principles and framework *and* ISO 14044 - Environmental management – Life cycle assessment – Requirements and guidelines

As mentioned in the previous section, ISO 14040:2006 and ISO 14044:2006 are the results of a process of standardisation which started in 1993 by the ISO and culminated in 2006 with the publication of these guidelines, which are still the most recognized for conducting LCA. Both documents complement each other, as the ISO 14040 provides the "principles and framework for LCA" (International Organization for Standardization, 2006a); while the ISO 14044 is the one that specifies "requirements and guidelines" (International Organization for Standardization, 2006b). Furthermore, these documents are usually the base for some of the other methodologies that will be later detailed. However, it is important to note that, while these documents offer general guidelines, there is no single prescriptive method for conducting LCA. The flexibility of LCA allows companies and organisations to adapt the methodology to their specific needs.

Principles

By using a life cycle perspective, an environmental focus, and an iterative approach, the LCA approach encompasses several key principles. The first requires the assessment to consider the entire life cycle of a product "from raw material extraction and acquisition […] to end-of-life treatment and final disposal" (International Organization for Standardization, 2006a). The environmental focus principle ensures that the LCA process is specifically geared towards assessing the product's environmental sustainability, without including social and economic factors. As for the latter, an iterative process provokes the results of each phase to be used as inputs for the next phase, thereby ensuring that the process is constantly refined and improved.

Phases

According to ISO 14040, the LCA should be divided into four different phases: goal and scope definition, life-cycle inventory (LCI), life-cycle impact assessment (LCIA) and interpretation. As per the principle of iteration, these phases are interconnected, and multiple iterations are required to achieve satisfactory results in the LCA process. Figure 2 provides a visual representation of this iterative process.

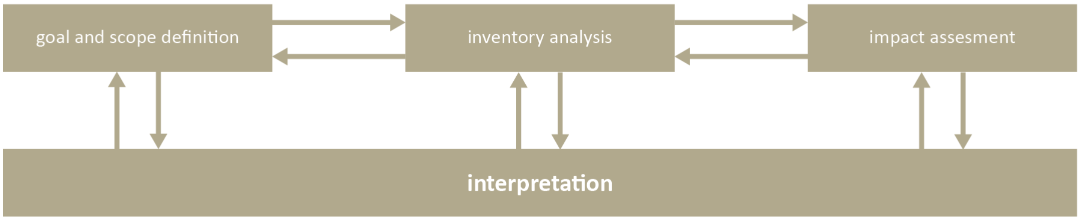

Figure 2: Stages of an LCA, based on ISO 14040 (International Organization for Standardization, 2006a).

Goal and scope

The goal and scope definition phase of an LCA requires several specific pieces of information to be specified. Firstly, it is important to clearly state the goal of the LCA, specifying the intended application, the audience, and the reasons for performing the study. Additionally, the scope should contain more specific information regarding the product or service to study and how this analysis will be conducted and any limitations.

It is critical to include in the scope a proper functional unit (FU). Not only needs to be clearly defined and measurable, but it needs to ensure the comparability of the results as well. Furthermore, it is important to set the boundaries that will be considered for the system. These will be defined by the unit processes that are going to be included.

In addition, other considerations might be as well specified in this section, such as the definition of study scenarios, when applicable, setting the data quality requirements or the need for a critical review is important. The allocation procedures that will be considered should also be specified in this phase. By addressing all these key aspects in the goal and scope definition phase, the LCA will be established for the subsequent phases.

Life-Cycle Inventory (LCI)

The primary objective of the LCI is to quantify the inputs and outputs of the system under evaluation. It should be as well aligned with the previously defined goal. This phase involves two distinct actions: data collection and calculation procedures to complete the data required. To achieve this goal, data collection must be meticulous and comprehensive, encompassing all the relevant unit processes within the system boundaries and with a detailed description of each one of them. This includes capturing data on energy inputs, materials, emissions, and other relevant parameters. Once collected, they must undergo rigorous validation and they posteriorly need to be related to the unit processes and reference flows.

The diagram included in Figure 3 illustrates the various stages involved in the inventory process, providing a clear overview of the sequential steps required to complete it.

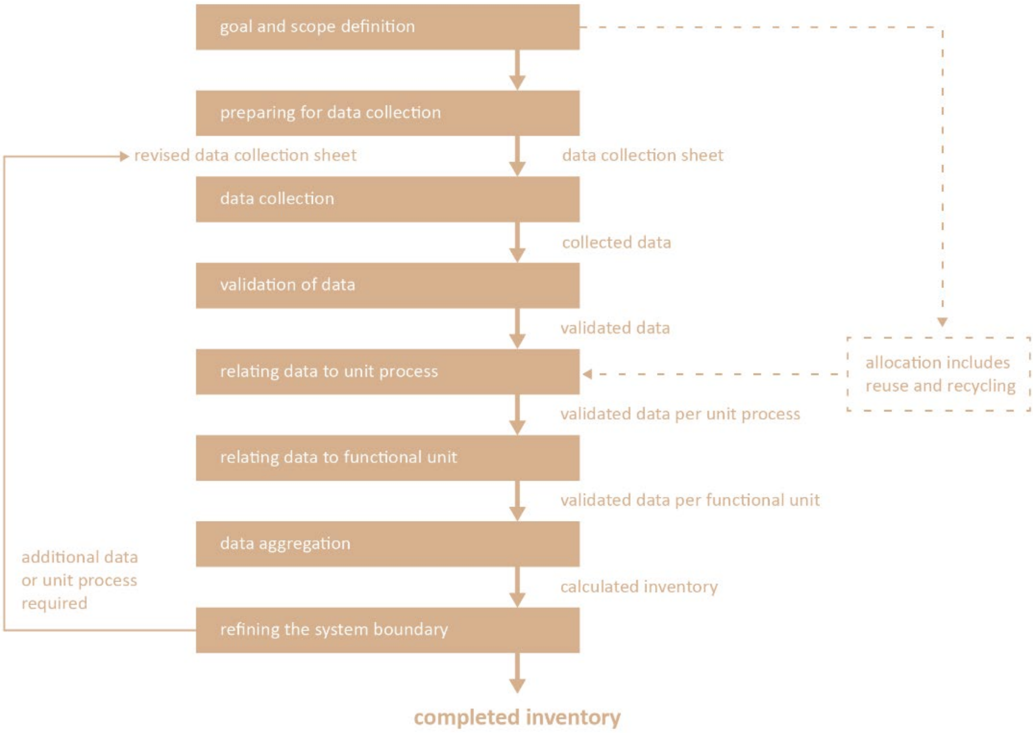

Figure 3: Simplified procedures for inventory analysis, based on ISO 14044 (International Organization for Standardization, 2006b).

Life-Cycle Impact Assessment (LCIA)

After obtaining LCI results, the next step is to associate them with environmental categories and indicators in the LCIA phase. While there are internationally accepted impact categories that are commonly used, such as Global Warming Potential (GWP), Acidification Potential (AP) or Eutrophication Potential (EP), these may vary depending on the needs of the person conducting the LCA. As it will be explained, other LCA methodologies specify a series of impact categories that should be included in the assessments. Additionally, it is important as well to identify and define each impact category, along with the corresponding assigned LCI, to ensure transparency of the calculations.

The process of assigning LCI results to impact categories is known as classification, while the calculation of the results for each category indicator is called characterisation. These two procedures are mandatory. However, this phase introduces some degree of subjectivity and presents certain limitations, such as the lack of spatial and temporal dimensions or the absence of a generally accepted LCIA method.

Figure 4 provides an illustration of the category indicator concept.

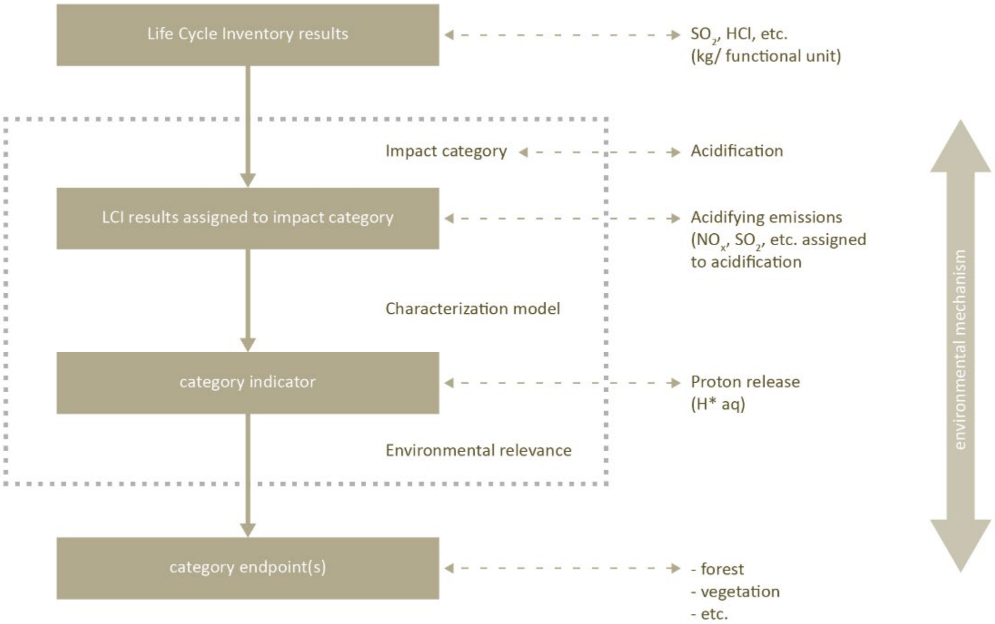

Figure 4: Concept of category indicator, based on ISO 14044 (International Organization for Standardization, 2006b).

Additionally, there are optional elements that may be considered: normalisation, grouping, weighting, and data quality analysis. Normalisation presents the results relative to a reference value, while grouping ranks or categorizes the impact categories according to certain criteria. Weighting involves assigning values to convert the results, and data quality analysis examines the robustness of the data through techniques such as uncertainty or sensitivity analysis.

Interpretation

Interpretation of the results is critical in evaluating the environmental impacts of the product, or process, studied. It involves reviewing and revising the results obtained LCI and LCIA phases to provide consistent results, while also identifying limitations and potential recommendations. A systematic approach is necessary for the interpretation phase to ensure that the limitations and uncertainties are communicated transparently. This approach identifies, qualifies, checks, evaluates, and presents the conclusions based on the findings of the previous steps, as described in the goal and scope of the study. The iterative process of reviewing and revising is integral to LCA, as the findings from this phase may lead to further revision of the LCI and LCIA.

Furthermore, another important consideration according to ISO 14040, when interpreting the results, is that reducing the findings to a single overall score or number is not scientifically justifiable, as it requires subjective value choices that depend on the application and context of the study.

Other steps

After completing the LCA, the following step is to prepare a comprehensive report that communicates the study findings effectively, covering all phases of the study and their respective considerations. It should be detailed enough to be informative and appropriately adapted to the target audience. The format of the report and the type should be specified in the scope stage.

Once the report is finalized, it should be critically reviewed to ensure it meets all the requirements. This could be conducted internally or externally, but it is essential to increase the credibility of the LCA and facilitate a better understanding of its results.

ISO 21931-1 - Sustainability in buildings and civil engineering works - Part 1: Buildings

ISO 21931-1 (International Organization for Standardization, 2022) is a standard that addresses sustainability in the built environment. This standard encompasses all three dimensions of sustainability: environmental, economic, and social. However, for this analysis, the focus will be on the environmental dimension. It is part of a group of documents dealing with sustainability in building construction and it shall be used in conjunction with other ISO documents, such as ISO 14040 and 14044.

The objective of this standard is to create a common framework for the assessment of sustainability in buildings. In doing so, it seeks to overcome the differences in regional and national methods for assessing sustainability and bridge the gap between them by creating a basis for such an assessment. It should be noted that ISO 21931-1 is not a methodology but a framework on which potential assessment methods can be based. The scope of ISO 21931-1 extends to both new constructions and refurbishments and covers the assessment of the building and its external works on the site.

Object of assessment

The assessment process begins by defining its object. The building can be described in various ways, such as a place to live, a part of the built environment, or an economic asset. This definition will affect the results and impacts of the assessment. Additionally, the system boundaries should be established, specifying the physical, temporal, and geographical limits of the assessment, emphasising the consideration of the same system boundaries with assessment comparisons.

The life stages of the building are grouped into pre-use, use, and end-of-life (A, B, and C). Supplementary information, including potential benefits and burdens, may be considered within the building assessment as module D. Certain subgroups are included within the four groups mentioned in Figure 4. A full description of the information included in each of these modules can be found in the document.

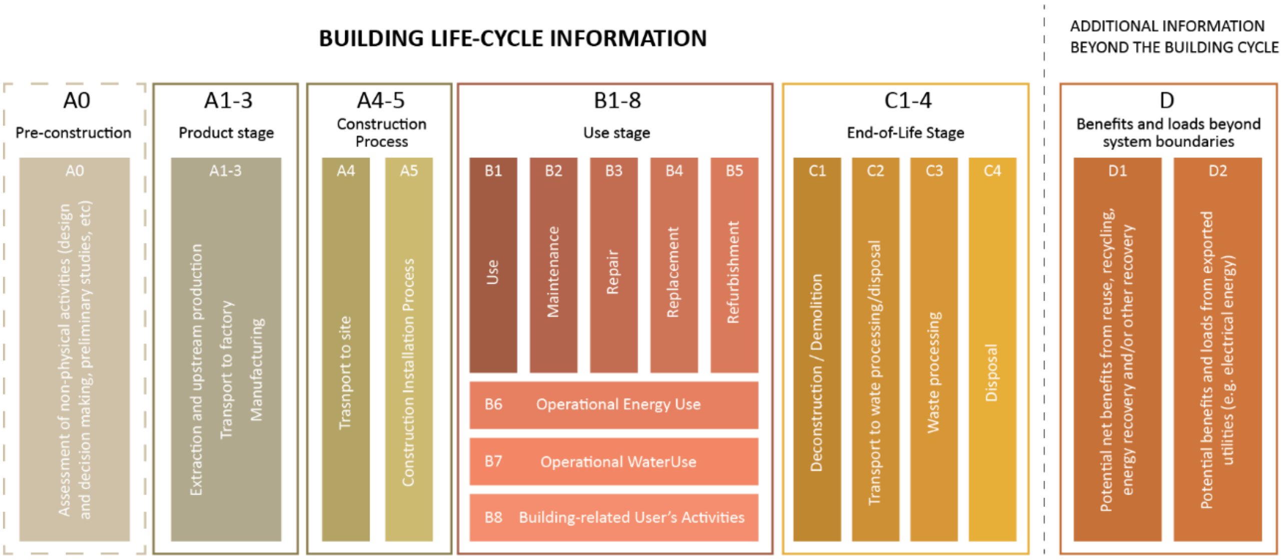

Figure 5: Building assessment information modules, based on ISO 21931-1 (International Organization for Standardization, 2022).

The functional equivalent of the building should also be established in this phase, including information such as building type, relevant technical information, the pattern of use, and reference unit. The assessment process is open to certain client requests if needed. Additionally, the way of accounting for the required service life (ReqSL) and the Design Life is an open process, if not specified by clients or regulations.

Framework for methods of assessment
In this section, minimum requirements for assessment methods are specified. In the first part, they specify the minimum information the documentation must have, as well as the obligatoriness of stating the purpose of the assessment and the assumptions and scenarios.

A list of issues related to each of the three sustainability aspects is also presented. Regarding the environmental dimension, the assessment methods must include structured lists of potential environmental impacts and environmental aspects. The environmental impacts must include global warming potential (GWP), depletion of the stratospheric ozone layer (ODP), acidification of water and land (AP), eutrophication (EP), and formation of tropospheric ozone (POCP). If information is available, resource depletion and human toxicity should also be included. Local environmental aspects, such as impacts on biodiversity, local infrastructure, microclimate, and surface drainage, must as well be considered.

Focusing on the environmental aspects, assessment methods should include the use of renewable and non-renewable sources, production, and segregation of waste for disposal, and land use related to the building site. They should address emissions to air, surface water, groundwater, and soil for local environmental aspects as well.

Methods for quantification
This section first addresses the data used. Regarding data sources, assessment methods for new buildings and refurbishments are differentiated, basing the data for new buildings on predictions and simulations, while for refurbishments, data collected from the building can also be included.

For environmental performance, it is recommended to prioritize field survey data over generic data, when available. Alternatively, Environmental Product Declarations (EPDs) are suggested as a data source, taken them with caution to ensure data is consistent with the scope of the assessment. If EPD information is not available, other data may be used if it is compliant with ISO 21930. Additionally, requirements for data quality should be set, and sensitivity analysis and/or probabilistic analysis might be necessary to ensure the reliability of the data. Moreover, the standard contemplates the option of adding performance levels to evaluate results, which can be based on building codes or regulations, user requirements, or targets based on research.

Finally, weighting and aggregating may also be considered as a method to evaluate the sustainability performance of a building. If used, the factors considered should be documented along with the aggregation method and they should be based on national, regional, or local contexts and justified.

Evaluation of assessment results and assessment report
The evaluation of results can be achieved using single scores or descriptors, as long as the values used to obtain them are identified. Additionally, following ISO 21930 (International Organization for Standardization, 2017b), the results from module D should never be aggregated with the results from the other modules.

The standard describes the minimum requirements for the reports containing the assessments, which can be found in section 9. Some of these requirements include information on the building’s location, function, materials, and systems, as well as the methodology used for the assessment and the data sources employed.

EN 15978 - Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method.

EN 15978 is a European standard developed by the European Committee for Standardisation (CEN), which was first published in 2011. It provides a framework for the assessment of the environmental impact of buildings. The document is fully compliant with the principles and requirements outlined in ISO 14040-44.

The assessment approach covers all building life cycle stages, using data from scientific and standardized EPDs (European Committee for Standardization, 2011). EPDs are documents that communicate quantified environmental information, including energy and resource consumption, environmental impacts, and health-related emissions of products or services, which have the purpose of facilitating environmental performance assessment and comparison. The standard EN15804 (European Committee for Standardization, 2021) provides the necessary information and guidelines for calculating EPDs of construction products.

Following a similar process to the ISO 14040, the standard is implemented. The first step is to describe the object of assessment, followed by the establishment of a system boundary that applies at the building level and the need to determine the procedure to be used for the inventory analysis. Once these initial steps are complete, a list of indicators and procedures for calculating them is established, outlining the requirements as well for the presentation of results, and the data necessary for the calculation.

Purpose and object of assessment

The first two stages of the assessment, which are equivalent to the Goal and Scope stages from ISO 14040 (International Organization for Standardization, 2006a), establish the objective of the assessment and its intended use, determining the functional equivalent as well. This should include at least the building type, relevant technical, functional requirements, pattern of use, and ReqSL, and it is the basis for comparison of the assessments.

Additionally, the reference study period (RSP) is established, which defaults to the ReqSL of the building. If the RSP is shorter than the ReqSL, the results are proportionally scaled down. On the other hand, if the RSP is longer than the ReqSL, it is necessary to consider the possibility of building renovation or refurbishment, and the associated impacts.

Finally, in this section, the system boundaries are established, following the modular structure of information presented in the EPDs (European Committee for Standardization, 2021) and similar to those on ISO 21931-1 (International Organization for Standardization, 2022), as shown in Figure 6. It is worth mentioning that EN15978 does not include module B8, which pertains to the assessment of users' activities and was considered optional in ISO 21931-1 (International Organization for Standardization, 2022).

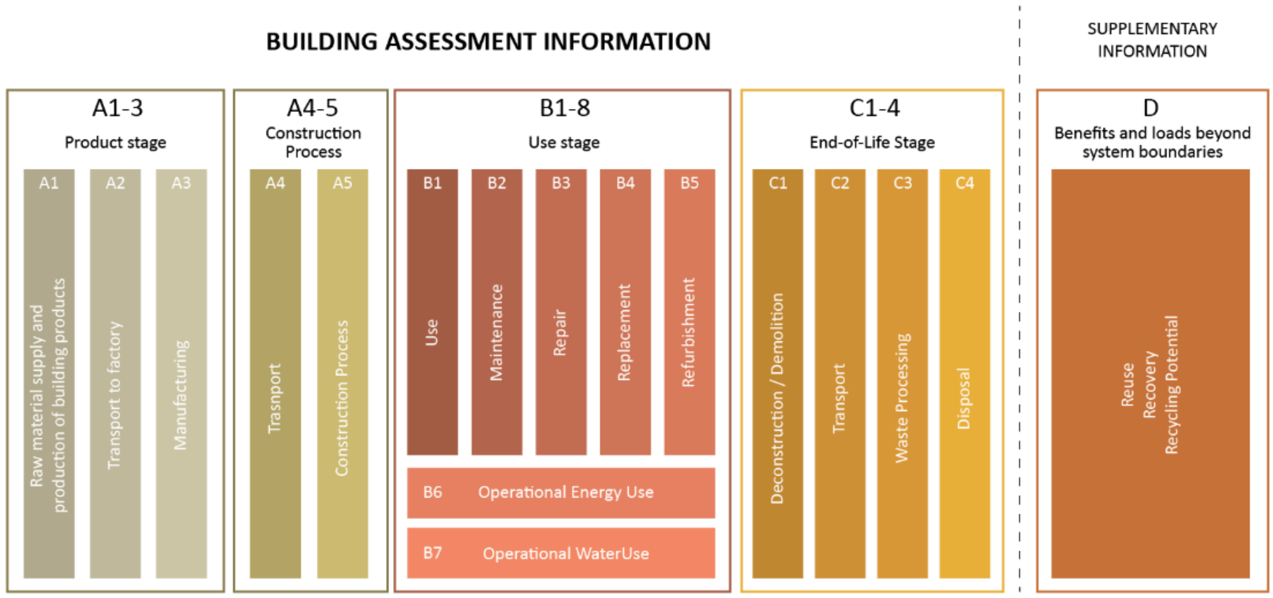

Figure 6: System boundaries according to EN15978 (European Committee for Standardization, 2011).

There are different types of EPDs depending on the life stages they cover (European Committee for Standardization, 2021), namely:

- Cradle to gate (A1–A3).
- Cradle to gate with options (A1–A3 + additional modules).
- Cradle to gate with modules C and D (A1–A3, + C + D).
- Cradle to gate with options, modules C and D (A1–A3 + C + D + additional modules).
- Cradle to grave and module D (A + B + C + D).

Scenarios for the building life cycle and quantification
In this stage, the building is deconstructed into its different parts and related processes, as well as describing its characteristics. This model serves as the basis for the assessment, enabling the different scenarios to be built based on EPDs. It is necessary to study the type of EPDs available and supplement the information with other sources as needed, and all documentation should be transparent.

It is important to consider time-related characteristics. This includes periodic operations, such as maintenance, replacement, and cleaning, calculating the number of replacements based on the lifespan of the product and the study period, with no partial replacements allowed. Taking these factors into account helps to ensure a thorough assessment of the building's environmental impact throughout the whole life cycle.

Selection of environmental data
The next step is to select the data that will be used for the calculations. As mentioned before, the EPDs serve as the main source of information. However, where relevant data is missing, information from carefully selected sources can be obtained.

Such sources must be accurately documented as well as their quality assessed. If the EPDs are done following EN 15804, it is understood that the quality is enough. Nevertheless, if data is sourced from other means, the standard sets certain minimum requirements to guarantee its quality. For example, data must not be older than 10 years, it must be based on one-year averaged data, and emissions should be accounted for at least 100 years.

Calculation of environmental data
Like the LCIA phase in ISO 14040-44, this section of the assessment calculates the environmental impacts and aspects resulting from the object of evaluation. The standard provides a series of predetermined indicators. Those describing environmental impacts and resource use are listed in Table 1 and

Table 2, along with their units. Additionally, the standard presents the impacts describing resource use, waste categories and the output flows leaving the system. The results are then calculated by multiplying the quantities obtained in the building modelling for each module by the value of the environmental indicators used.

Table 1: Indicators describing environmental impacts (European Committee for Standardization, 2011).

Indicator	**Unit**
Global warming potential, GWP	kg CO_2 equiv.
Depletion potential of the stratospheric ozone layer, ODP	kg CFC 11 equiv.
Acidification potential of land and water; AP	kg SO_2- equiv.
Eutrophication potential, EP	kg $(PO_4)^3$ - equiv.
Formation potential of tropospheric ozone photochemical oxidants, POCP	kg Ethene equiv.
Abiotic Resource Depletion Potential for elements, ADP_elements	kg Sb equiv.
Abiotic Resource Depletion Potential of fossil fuels, ADP_fossil fuels	MJ, net calorific value

Table 2: Indicators describing resource use (European Committee for Standardization, 2011).

Indicator	Unit
Use of renewable primary energy, excluding energy resources used as raw material	MJ, net calorific value
Use of renewable primary energy used as raw material	MJ, net calorific value
Use of non-renewable primary energy, excluding energy resources used as raw material	MJ, net calorific value
Use of non-renewable primary energy used as raw material	MJ, net calorific value
Use of secondary material	kg
Use of renewable secondary fuels	MJ
Use of non-renewable secondary fuels	MJ
Net use of fresh water	m^3

Reporting, communication, and verification
The final stage of the assessment involves reporting the results, which must adhere to a set of minimum requirements specified in the standard. However, the most crucial aspect emphasized in this section is the way results are presented. The total values from each module should be stated in the report, and if any module fails to yield results, it should be mentioned. This standard does not contemplate the possibility of normalising or weighting the results, nor does it mention the possibility of presenting them as a single score value. Additionally, the standard also provides for the possibility of verifying the results obtained. Certain aspects, along with the verifier's competence, must be included in this process.

PEF – Product Environmental Footprint method

The European Commission decided to elaborate a common way of measuring the environmental performance of products and organisation, because of the existence of multiple methodologies and systems to perform environmental assessments. This led to the creation of two distinct methods based on LCA: the Product Environmental Footprint (PEF) and the Organisation Environmental Footprint (OEF) (European Commission, 2021).

The PEF method is designed to evaluate the environmental impact of a specific product throughout its life cycle, while the OEF method assesses the overall environmental performance of an organisation. The adoption of these methods aims to promote more sustainable practices informing consumers and stakeholders about the environmental impact of products and organisations, as well as obtaining more robust and comparable results.

Furthermore, to account for the unique characteristics of certain sectors, specific Product Environmental Footprint Category Rules (PEFCRs) and Organisation Environmental Footprint Sector Rules (OEFSRs) have been developed. These rule sets provide detailed guidance on how to calculate the environmental footprint of a particular product group and are applicable throughout the entire EU market (PRé Sustainability, 2023).

To help practitioners navigate the differences between the PEF and OEF methods and the ISO 14040-44 documents, the European Commission published a guide titled "Understanding Product Environmental Footprint and Organisation Environmental Footprint methods" (Damiani et al., 2022) and the differences will be summarized in the following sections, considering the stages of the LCA process.

Goal and Scope definition
In the Goal and Scope stage, the main difference between this document and the ISO is the clarification of the structure of the FU (Damiani et al., 2022). The PEF method requires the FU to "answer" the following questions:

- What function is being provided?
- How much of that function is being provided?
- How long the function is being provided for?
- How well the function is being provided?

Inventory Analysis

In the Inventory Analysis phase, there are significant changes in two main aspects of the PEF method: how inventory modelling should be conducted, and the quality of the data used.

In terms of inventory modelling, the PEF method establishes a series of mandatory life stages that need to be included in all Environmental Footprint studies: the raw material acquisition and pre-processing, manufacturing, distribution, use stage and end of life. This method exempts certain specific products, like intermediate products, from some of these stages.

Another significant consideration in the PEF method is the modelling of waste and recycled materials. Unlike the ISO standard, which provides vague and limited information, the PEF method specifies the Circular Footprint Formula (CFF). The purpose of this formula is to share the environmental burdens and benefits of using recycled materials between suppliers and users by introducing certain parameters based on the demand and offer in the market. The CFF consists of three parts: the use and supply of materials, recovery of energy and disposal formula. First, the material part applies to stages where recycled material replaces virgin raw materials. Second, the energy part of the formula relates to the quantity of material used for energy recovery at the end of life, and third, the disposal part calculates the emissions and resources used in the disposal process.

The PEF method places strict requirements on the quality of the data used in EF studies. The data should follow a specific structure, nomenclature, and modelling rules to ensure EF compliance. Additionally, the method prioritizes the use of primary data, such as company and site-specific information, over secondary data, such as databases or literature. The quality of the data is evaluated based on a score from 1 to 5 across four categories, ranging from excellent to poor. To achieve a high-quality score, primary data must have a score of less than 1.5, while secondary data should have a score of no more than 3.0.

Impact Assessment

For the Impact Assessment phase, the document specifies sixteen impact categories that must be considered: climate change, particular matter, ionising radiation, photochemical ozone formation, acidification, ozone depletion, eutrophication (terrestrial, marine, freshwater), ecotoxicity (freshwater), human toxicity (cancer, non-cancer), land use, water use, resource use (minerals and metals, fossils).

In addition, the PEF method requires four mandatory steps to be completed during the Inventory Analysis phase. First, classification and characterisation are included, similar to ISO 14040-44, with the addition of normalisation and weighting as mandatory steps. The values used for these two processes are provided in the method. Consequently, the results are presented as a single score "for marketing and comparative assertions" (Damiani et al., 2022). However, this approach directly contradicts the ISO document, which states that reducing the results to a single score is not scientifically justifiable (International Organization for Standardization, 2006b).

Other steps

There are other differences to be noted, including aspects such as the minimum requirements for reviewers or review panels during the verification stage, or the type of analysis to be included in the interpretation phase. However, the differences outlined earlier are deemed to be the most significant, as they represent the biggest changes from the documents that served as the basis.

Level(s) – EU Framework

Overview of the framework

Level(s) is a voluntary framework developed by the Joint Research Centre (JRC) of the European Commission, launched in 2017 in its beta versions and officially released in its final version in 2020. It provides a framework for assessing sustainability in buildings in the European Union, providing a common language for all the stakeholders involved. This framework applies to residential and office buildings, both for new newly designed buildings and renovation projects.

Level(s) framework aims at promoting the whole life cycle approach by conducting an LCA, allowing for an analysis of the full range of the impacts and the identification of the most significant ones, the "hot spots".

Three different assessment levels are distinguished, depending on the stage of the project: level 1, conceptual design; level 2, detailed design, and construction stages; and, level 3, as built and in use stages. These levels progress from qualitative to quantitative and finally to monitoring assessments, which increases accuracy and reliability.

The framework is structured including six macro-objectives, which describe what the strategic priorities for buildings should be for the European Union and the Member States in different areas. To measure the performance of a building within these objectives, in total 16 core indicators were developed. The macro-objectives, the core indicators, and the units of measurement for each of them can be found in Table 3.

Table 3: Overview of the macro-objectives, their indicators, and units of measurement (Dodd et al., 2021a).

Macro-objective	Indicator	Unit
1. GHG and air pollutant emissions along a building's life cycle	1.1. Use stage energy performance	$kWh/m^2/year$
	1.2 Life cycle GWP	$kgCO_2$-eq/m^2/year
2. Resource efficient and circular material life cycles	2.1 Bill of quantities, materials, and lifespans	Unit quantities, mass, and years
	2.2 Construction & demolition waste and materials	kg of waste and materials per m^2 of useful floor area
	2.3 Design for adaptability and renovation	Adaptability score
	2.4 Design for deconstruction, reuse, and recycling	Deconstruction score
3. Efficient use of water resources	3.1 Use stage water consumption	m^3/year/occupant
4. Healthy and comfortable spaces	4.1 Indoor air quality	Parameters for ventilation, CO_2 and humidity. Target list of pollutants: TVOC, formaldehyde, CMR VOC, LCI ratio, mould, benzene, particulates, radon
	4.2 Time outside of thermal comfort range	Percentage of time out of range during heating and cooling seasons
	4.3 Lighting and visual comfort	Level 1 checklist
	4.4 Acoustics and protection against noise	Level 1 checklist
5. Adaptation and resilience to climate change	5.1 Protection of occupier health and thermal comfort	Projected percentage of timeout of range in the years 2030 and 2050
	5.2 Increased risk of extreme weather events	Level 1 checklist
	5.3 Increased risk of flood events	Level 1 checklist
6. Optimised life cycle cost and value	6.1 Life cycle costs	€/m^2/year
	6.2 Value creation and risk exposure	Level 1 checklist

Level(s) is built upon four Key Concepts:

1. Whole life cycle and circular thinking: Considering this holistic of approach, it is possible to identify "hot spots" which can be the starting point for potential optimisations.
2. Closing the gap between design and actual performance: Level(s) ensures that not only the design stages are considered by the inclusion of Level 3 as-built assessment. This approach bridges potential gaps between design intent and real-world performance.
3. Achieving Sustainable Renovation: The framework provides specific instructions for renovation projects, encouraging a comprehensive approach to them.
4. Positive Influence in the Market Value: Level(s) aims to demonstrate that consideration of sustainability in buildings has a positive influence on the market value of properties.

Level(s) is not a certification scheme as it lacks benchmarking values. Instead, it provides an open-source tool, functioning though a framework developed to facilitate sustainability assessment and increase the comparability of the results. It additionally offers comprehensive user manuals to guide practitioners effectively.

Life-Cycle Analysis (LCA) considerations

The framework recommends establishing a project plan as the first step, which should include the following content (Dodd et al., 2021b):

- It is necessary to define which macro-objectives and core indicators are used to assess the performance.
- Clearly establish which level is assessed, fixing the level of commitment for the stakeholders.
- Plan which resources are necessary to dedicate to the assessment and when they are going to be necessary.

In Levels 2 and 3, one of the mandatory steps is including a building description providing the information detailed in Table 4.

Table 4: Mandatory steps to be included in the building description (Dodd et al., 2021b).

Description	Information Required
1. Location and climate	1.1 The country and region in which the building is located
	1.2 Heating and cooling degree days
	1.3 The climatic zone in which the building is located
2. The building typology and age	2.1 The project type
	2.2 The year of construction
	2.3 The market segment
3. How the building will be used	3.1 The intended conditions of use
	3.2 Building occupation and usage patterns
	3.3 The intended (or required) service life
4. The building model and characteristics	4.1 The building form
	4.2 The total useful floor area within the building and measurement standard used
	4.3 The scope of building elements to be assessed and categorisation system used

From this document, we can extract certain LCA indicators. The section titled "the building model and characteristics" contains information regarding a physical description of the building and the scope of building elements considered. Moreover, in the same section, it is possible to find the reference unit, as it states that the results should be normalized per m² of total useful floor area.

Moving forward to sections 2 and 3, it is possible to find the required technical characteristics and functionalities of the building crucial to find the FU. Finally, the service life is required by Level(s) to be calculated as 50 years.

Comparison of the methodologies

Through thorough analysis and synthesis of the methodologies, Table 5 to

Table 11 were generated to underscore the disparities among the various methodologies, capturing the variations in each of the LCA stages.

Prior studies have already undertaken similar comparisons, including one or more of the methodologies previously explained (Kanafani et al., 2019; Vandervaeren et al., 2022). Some of these have been the inspiration for extracting relevant points of comparison.

Table 5: Comparison of different LCA methodologies regarding Goal methodological aspects.

Aspect	ISO 14040-44	ISO 21931	EN 15978	PEF	Level(s)
Sustainability concerns addressed	Environmental aspects.	Environmental, social, and economic aspects.	Environmental aspects.	Environmental aspects.	Environmental, social, and economic aspects.
Application Area	Any product or service	Building and civil engineering works. Could be buildings, part of buildings or external works within site. Both new and existing buildings.	Building level. All building types, including new and existing buildings and refurbishment projects. List of building elements in Annex A.	Any product or service	Building level (Office and residential). Specified list of building parts categorised into Shell, Core, and External Works.
Goal	The goal, clearly defined and consistent with the application, should state the reasons and intended use of LCA results.	Goal definition establishes context for sustainability assessment and identifies its intended use in construction works.	Goal definition sets sustainability assessment context and determines its application in construction.	Goal definition is crucial for conducting PEF studies, identifying audiences, reasons, and potential comparisons.	The “goal and scope” should include the following information: intended use of the building, FU, system boundary and building model. Standard calculation: all Stages included. Simplified option 1: A1-3+B4-6, Simplified option 2: A1-3+B6+C3-4+D

Table 6: Comparison of different LCA methodologies regarding Scope methodological aspects.

Aspect	ISO 14040-44	ISO 21931	EN 15978	PEF	Level(s)
Scope Definition	Defines scope in terms of product life cycle stages, from raw material acquisition or generation of natural resources to the end-of-life stage.	Environmental performance of buildings. It shall indicate the physical, temporal, and geographical limits. Pre-use, use, and end-of-life (A, B, and C). Module D might be considered. Module A0 is included and B8 is optional.	Covers the assessment of the environmental performance of buildings, considering a life cycle approach. Pre-use, use, and end-of-life (A, B, and C). Module D might be considered	Defines scope in terms of life cycle stages, from raw material acquisition to end-of-life, with a focus on environmental impacts.	Same as identified in Goal in Table 5.
System Boundaries	Broad system boundaries, including stages of the life cycle that the LCA evaluator considers important and data.	System boundaries are defined by the building's service life.	System boundaries include all stages of a building's life cycle.	Broad system boundaries, including all stages of the life cycle and multiple environmental impact categories.	In the standard calculation, it includes all stages in the life cycle with one, or multiple, environmental impact categories.
Functional Unit	It should be clear and defined by the user based on the purpose of the study. It should include the function, the extent of the function, expected level of quality and the lifetime of the product.	The FU is the building and its services	The FU is a building over its life cycle. It shall include, at east, the building type, relevant technical information, pattern of use and ReqSL.	It should be clear and defined by the user based on the purpose of the study. It should include the function, the extent of the function, the expected level of quality, and the duration/lifetime of the product.	Results must be expressed per m^2 of total useful floor area over a 50-year period.
Time Scale	Time frame might vary depending on the goal and scope definition	Open process, unless specified by clients or regulations	ReqSL of the building is the default. Results can be scaled to different periods.	Not defined. It depends on the product.	50 years
Decarbonisation of the electricity grid	It can be included in the goal definition.	Not defined, but it could be allowed in the goal description.	Not defined, but it could be allowed in the goal description.	Includes the CFF to model recycling, which considers the market situation	It shall be considered.
Consideration for exported energy	Not defined, but it could be included in the goal definition.	Included in module D2.	It is reported separately.	Not defined.	It should be reported in module D.

Table 7: Comparison of different LCA methodologies regarding Data and Data Quality methodological aspects.

Aspect	ISO 14040-44	ISO 21931	EN 15978	PEF	Level(s)
Type of data and sources	No limitations in the sources of data. It should be in line with the goal and scope of the study. It can be measured, or estimated using recognized and specialised literature	Field survey data prioritised over generic data. EPDs can be used. If not available, other ISO 21930 compliant data may be used.	EPDs are the main source. Supplementary information from other sources can be used if needed. Different data sources can be used depending on the building stage the LCA is performed.	Primary data, such as company and site-specific information, is prioritized over secondary data, such as databases or literature.	Prioritize use specific data from EPDs. Use average data from specific production processes. Generic data might be used in certain scenarios.
Data quality requirements	Requirements for data quality are defined, and its assessment is required.	Emphasizes the need for appropriate data quality, but it does not provide specific requirements.	EPDs following EN 15804 are considered having enough quality. For other sources, it requires specific data quality requirements for building assessment.	It includes detailed requirements for data quality and its assessment, with the use of a data quality scale.	Data should meet EN15804 quality requirements. Other sources might be used, and minimum criteria are set. using a Data Quality Index.
Consideration for replacements	The FU should be consistent with the goal and scope of the study, which might include consideration of maintenance, repair, and replacement over the lifetime of a product or service. However, it does not provide specific guidelines on how to account for these aspects.	It does not specifically mention replacements of system components during the lifetime of a building. However, it is implied that these aspects should be considered as part of the life cycle stages.	Consideration of replacements in the use stage of a building's life cycle. The replacement of components (like windows, heating systems, etc.) that may not last as long as the building itself. Number of replacements considers the lifespan of the product and the study period. No partial replacements allowed.	The EF method considers the replacement of components as part of the use stage. The method requires that all significant environmental impacts in the product's life cycle are identified and quantified, including those related to the replacement of parts.	A table with expected lifespans is provided for different elements within each building part.

Table 8: Comparison of different LCA methodologies regarding Data Inventory methodological aspects.

Aspect	ISO 14040-44	ISO 21931	EN 15978	PEF	Level(s)
What should the inventory focus on the study?	The LCI involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. It should reflect the FU defined in the goal and scope. The data should be as specific as possible to the product system under study.	Collecting data on all inputs and outputs related to the life cycle of the building, reflecting the building's service life.	Collecting data on all inputs and outputs related to the life cycle of the building, reflecting the building's service life.	LCI involves collecting data on all inputs and outputs related to the life cycle of a product or organisation, reflecting the FU defined in the goal and scope. The data should be as specific as possible to the product system under study and should cover all relevant environmental impact categories.	Collecting data on all inputs and outputs related to the life cycle of the building, reflecting the building's service life.
Specificities in the production and construction stage		**A0**: list of activities included. **A1 to A3**: cradle to gate processes. **A4 and A5**: examples of processes to be included.	**A1 to A3** as in EN 15804. **A4 to A5**, includes a list of processes.		**A1 to A3**: follows the rules in EN 15978. **A4 to A5**: basic recommendation s provided.
Specificities in the use stage		**B1** basic specifications. **B2 and B3:** basic specifications. **B4**: considerations for planned replacements. **B5**: certain considerations specified for planned refurbishments. **B6**: certain systems and considerations to include. Includes energy to heat DHW. **B7**: certain considerations specified. **B8:** optional module	**B1:** basic considerations specified. **B2 to B4**: certain considerations specified. Service life planning according to ISO 15686. **B5**: typical scenarios according to building type. **B6**: general recommendation s. Energy use from EN15603. **B7**: certain considerations specified.		**B1 to B5**: generic processes to include are detailed. **B6**: list of potential processes to include is provided. **B7**: certain considerations specified.
Specificities in the End-of-Life stage		**C1 to C4**: specifications for each module.	**C1 to C4**: certain considerations specified for each module.	Specific formula to calculate the environmental benefits of recycling, the "end-of-life formula".	**C1 to C4**: certain considerations specified.
Specificities considering credits or benefits		**D1**: recovered materials. **D2:** exported energy.	Rules to calculate it according to EN 15804.		Certain considerations specified.

Table 9: Comparison of different LCA methodologies regarding Data and Allocation and Cut-off criteria methodological aspects.

Aspect	ISO 14040-44	ISO 21931	EN 15978	PEF	Level(s)
Allocation approach	Three-step possibilities in order of preference. Option 1: avoid allocation when possible. Option 2: allocate by physical relationships (e.g. mass). Option 3: allocate based on other criteria (e.g. economic value)	Not specified.	Not specified.	Follows the criteria from ISO 14044.	As in EN 15804.
Allocation approach for reused or recycled materials	Same principles apply, but additional elaboration is needed. Two procedures type are distinguished: open or closed loop.	Not specified.	As in EN 15804.	CFF to consider recycle materials substituting raw materials. Values are provided for some components of the formula. This applies to waste from products from each stage.	As in EN 15804.
Cut-off criteria	Does not provide specific cut-off rules. However, it recommends that any cut-off criteria should be clearly stated and justified.	It does not provide additional specific cut-off rules. It refers to ISO 14040-44 for the LCA methodology.	Cut-off according to EN 15804. In case of insufficient input data, 1 % renewable and non-renewable primary energy usage and 1 % of total mass input of that process. Total excluded input flows per module, can be maximum 5% of energy and mass.	Any process and flows excluded cannot account for more than 3% of the material or energy flow.	Same rules as in EN 15978 should be followed.

Table 10: Comparison of different LCA methodologies regarding LCIA methodological aspects.

Aspect	ISO 14040-44	ISO 21931	EN 15978	PEF	Level(s)
Environmental impact categories to be reported	Includes several mandatory and optional impact categories. The choice depends on the goal and scope of the study.	Does not provide specific methods for impact assessment but refers to ISO 14040-44 for this purpose. GWP, ODP, AP, EP, and POCP. If information is available, resource depletion and HT also included.	Uses a set of prescribed impact categories and indicators for buildings. These are mentioned in Table 2 in this document.	Provides specific methods for impact assessment, including 16 mandatory impact categories, specified in section 0.	GWP is mandatory. Other impacts might be included.
Characterisation model	No specific characterisation models. It provides a framework for conducting an LCIA, including the selection of impact categories, category indicators, and characterisation models. The choice of models is left to the user and should be consistent with the goal and scope of the study.	It refers to ISO 14040-44 for the methodological framework of the LCA, including the LCIA phase.	The choice of models to calculate the categories mentioned above is left to the user and should be consistent with the goal and scope of the study. Characterisation factors provided in Annex C in EN 15804	The Environmental Footprint (EF) method provides specific characterisation models for 16 mandatory impact categories	Values are provided in the document.
Biogenic carbon consideration	Does not provide specific guidelines on biogenic carbon. The consideration of biogenic carbon is left to the user and should be consistent with the goal and scope of the study.	Refers to ISO 14040-44 for LCA methodology. Does not provide additional specific guidelines on biogenic carbon.	Does not provide specific guidelines on biogenic carbon. Consideration of biogenic carbon is left to the user and should be consistent with the goal and scope of the study. In EN 15804, they follow the -1/+1 criteria (Hoxha et al., 2020).	Emissions of biogenic carbon dioxide are reported separately from other GHG emissions in the climate change impact category. The follow the 0/0 criteria. Biogenic methane must be reported separately (Hoxha et al., 2020).	Follow the -1/+1 criteria. Negative emissions from CO_2 storage are reported separately.

Table 11: Comparison of different LCA methodologies regarding LCI methodological aspects.

Aspect	ISO 14040-44	ISO 21931	EN 15978	PEF	Level(s)
Normalisation	Optional. If used, it should be transparently documented and justified.	Not specifically mentioned. Refers to ISO 14040-44 for LCA methodology.	Not specifically mentioned.	Mandatory. Normalisation references are provided for Europe.	Not specified.
Weighting	Optional. If used, it should be transparently documented and justified.	Not specifically mentioned. Refers to ISO 14040-44 for LCA methodology.	Not specifically mentioned.	Mandatory. Weighting values are provided for each environmental impact category.	Not specified.
Sensitivity analysis	Recommended to validate results and understand the influence of uncertainties.	Sensitivity analysis and/or probabilistic analysis might be considered. Refers to ISO 14040-44 for LCA methodology.	Not specifically mentioned.	Mandatory for comparative assertions, otherwise recommended.	Not specified.
Presentation of results	Should be transparent, complete, accurate, consistent, and relevant to the goal and scope of the study.	Should follow ISO 14040-44 guidelines.	Results should be presented per life cycle stage and per indicator.	Detailed requirements are provided for presenting results, including the use of specific formats and software tools.	Results presented in five groups of modules (A1-3, A4-5, B1-7, C1-4, and D) and per type of GWP.
Report of results	Should include a clear description of all elements defined in the goal and scope, including assumptions, limitations, and decisions made during the LCA study.	Should follow ISO 14040-44 guidelines.	Should include a clear description of the building, functional equivalent, system boundary, calculation rules, etc. Tables and minimum requirements provided.	Detailed requirements are provided for reporting results, including specific content and format requirements for EF studies.	Table is provided as a template for the reporting.
Review process	Requires critical review for comparative assertions intended to be disclosed to the public.	Does not provide specific requirements for review.	Review is optional but recommended for transparency and credibility	Requires third-party review for studies intended to support comparative assertions disclosed to the public.	An external review shall be conducted, but no requirements are provided.

2.2.2 Characteristics of daylighting systems impacting LCA performance

Two groups of characteristics determine the overall performance of the daylighting system: the physical properties and the building-dependant characteristics.

Physical Properties of Daylighting Systems

- **Material Selection**: The careful selection of materials affects their durability, impacting the refurbishment or replacement frequency. Additionally, it impacts the end-of-life scenario, including the recycling, or reusing, potential.
- **Glazing Type**: Decisions such as the number of glass layers, their thickness, if it contains a low-e coating, or which one is the filling gas, directly affect the daylighting performance, thermal properties, and environmental impacts.
- **Opaque Material**: The choice of the opaque materials, including the window frames or the reflectors in the Tubular Daylight Devices (TDD), directly impacts the energy efficiency of the system and has direct environmental implications.
- **Shading Characteristics**: Choices in the type of shading, the material, or the size affect the system performance and the material quantities.
- **Size**: The height, width and depth of the system crucially affect the performance and environmental impact.
- **Geometry**: The shape of the system impacts the thermal and daylight performance.

Building-dependant Characteristics

- **Window-to-wall Ratio (WWR):** The relation between the window and the area it is placed on impacts the amount of radiation and daylight inside the building, varying the heat losses through the envelope and the material quantities.
- **Building Plan:** The configuration of the room, including aspects such as the floor depth, directly impact the daylight accessibility, as areas further from wall openings may receive insufficient daylight, causing a need to increase the openings.
- **Room Surface Characteristics:** The materials in the room and their reflectance impact the distribution of daylight in a space. Highly reflective surfaces enable daylight to penetrate, resulting in smaller openings to achieve similar results.
- **Surrounding Context:** External factors, such as neighbouring structures and their projected shadows, play a role in limiting daylight access.
- **Building Height:** Higher floors usually benefit from increased daylight because of the lower density of external obstacles.
- **Orientation:** This affects the radiation received, potential daylight, heat gains (or losses) and the potential need for shading systems.
- **Location:** The geographical position has a similar influence as the orientation.

Additional Aspects

Performance Characteristics

- **G-value**: Affects energy performance with different implications in winter and summer.
- **Visual transmittance**: It varies the amount of light entering the building, impacting electric lighting consumption and the occupants' wellbeing.

Life Cycle Actions

- **Maintenance Frequency**: A frequent and careful maintenance extends the lifespan of the products, reducing the need for replacement or repairs.

3 Harmonised methodology for a new daylight system

Following the same structure detailed in the ISO standards 14040/44:2006, the proposed harmonised LCA methodology aims to assess the environmental life cycle performance of daylighting systems in buildings, providing practical guidance for practitioners in the field.

The initial stage describes the Goal and Scope of the assessment. This section underlines the study's objectives, setting the boundaries for the assessment, including the definition of the FU and the definition of the scenarios for system use. In addition, this section includes the specific technical aspects of the daylighting system to be assessed and the baseline considered, encompassing aspects such as dimensions, material characteristics, visual transmission of the system, or the elements in the room. Following, the LCI stage explains the methodology's principles, specifying data requirements, quality standards, allocation procedures, recycling considerations, cut-off criteria, and simulation parameters, focusing big on collecting foreground and background data for the use phase.

The LCIA focuses on environmental impact categories, centring the attention on the climate change category, measured by the GWP100 indicator. Finally, the methodology concludes with the interpretation stage, where results are thoroughly analysed. This involves a deep exploration of the interrelations between different aspects within the daylighting systems and includes recommendations for uncertainty and sensitivity analysis to enhance the robustness of our conclusions. To increase understanding of the harmonised methodology, Table 12 contains the key aspects that are further developed in the next stages.

Table 12: Summary of the key aspects in the proposed harmonised methodology.

Stage	Topic	Description
Goal and Scope	*Goal*	Evaluate environmental impacts of daylighting systems, focusing on the use stage
	System Boundaries	Cradle-to-grave evaluation
	Functional Unit	kWh of primary energy consumption difference compared to a baseline in a space with a minimum DFm of 1% over a 50-year period
	System Characteristics	Minimum aspects to describe for each system assessed
	Baseline Description	Technical characteristics of the baseline system, based on the average EU window
LCI	*Type of Data*	Foreground and background data, emphasising use phase
	Data Quality Requirements	Adherence to EN 15804 and use of Data Quality Index
	Allocation Procedures and Recycling	Consideration of recycling and circularity aspects
	Cut-off Criteria	Criteria based on mass, energy, or environmental significance
	Simulation Parameters	EN 17037 as base for daylight simulations. Values for the energy simulations can be based on the standard values from ASHRAE 90.1-2019 or any geographically relevant source.
LCIA	*Environmental Impact Categories*	Climate change category using GWP100 indicator
	Characterisation Model	GWP100 from the latest IPCC Assessment Report
Life Cycle Interpretation	*Analysis of the Results*	Thorough examination of environmental impacts. Minimum results to report on environmental impacts, daylight performance results, indoor thermal comfort, energy results and GWP values.
	Aggregation Method	No need for weighting and normalisation
	Uncertainty and Sensitivity Analysis	Recommended sensitivity analysis, e.g., Monte Carlo simulation

3.1. Goal and Scope

3.1.1 Goal

The aim of the study is to evaluate the potential environmental impacts associated with the use of daylighting systems. These systems aim to reduce reliance on electric lighting and improve the occupants' visual comfort, resulting in energy savings and increased wellbeing throughout their lifespan. Applicable in diverse settings, from residential to commercial and institutional buildings, the daylighting system's comprehensive life cycle impact evaluation intends to cover all stages.

This section provides a flexible framework, allowing the researcher to define any elements deemed necessary to achieve the broader goal of the assessment, including but not limited to:

- Description of the baseline system, especially relevant when the aim is to compare several systems.
- The main parameters or characteristics necessary to scale the systems to the same functionality.
- Identification of key environmental hotspots
- Energy source scenarios considered during the use of the system. Considerations for future decarbonisation of the electricity grid can be considered, but it must be clearly stated.
- Clear specification of scenarios for each module, focusing specially on the use phase: maintenance, repair, replacement, and potential refurbishment of the system (LCA modules B2 to B5).

3.1.2. Scope

System boundaries

The system boundaries adopt a Cradle-to-Grave approach to assess the daylighting system's environmental impact comprehensively, incorporating all life cycle modules detailed in EN 15978 (European Committee for Standardization, 2011) The benefits and load beyond the system boundaries, if included, must be reported separately (module D). These system boundaries encompass all stages, from manufacturing to decommissioning and end-of-life considerations, as graphically summarized in Figure 7.

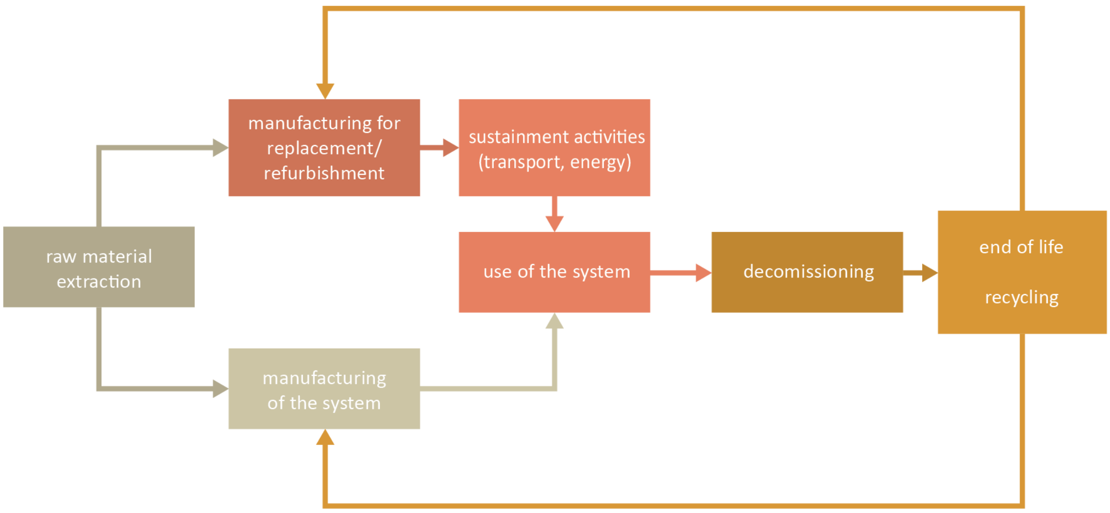

Figure 7: Overview of the flows involved in the LCA.

Functional Unit (FU)

Conventional LCAs for daylighting systems evaluate their performance normalised "per m² of system" or "per m² of floor area". Some studies go further considering comparable thermal performance, consistent study frames and even considering the influence of the energy performance of the space (Carlisle & Friedlander, 2016; Kowalczyk et al., 2023). However, these approaches commonly fail to include the main aspect that these systems provide: daylight.

For that reason, this methodology defines the FU as the "kWh of primary energy consumption difference compared to a baseline in a space with a minimum DFm of 1% over a 50-year period", "answering" the questions stated in the Product Environmental Footprint: what, how much, how well and how long (Damiani et al., 2022). Additionally, it encapsulates three of the aspects that were considered critical in the assessment of daylighting systems: energy consumption, material lifespan, and daylight quality.

First, it considers the energy difference through the variation in the envelope performance, in terms of energy losses and solar gains. Second, by setting a fixed timeframe of 50 years, as stipulated in Level(s) Framework (Dodd et al., 2021a), the proposed methodology ensures a comprehensive consideration of the estimated system service life over the complete building life cycle.

Lastly, by setting a minimum daylight provision threshold, it is ensured that the space meets a minimum daylight quality, regardless of the potential daylight requirements stipulated in the country of the assessment. The choice of the DF as the required metrics is based on the Swedish regulations, which establish a minimum point Daylight Factor (DFp) or Daylight Factor median (DFm) of 1% (LINK IO, 2021). Here, the emphasis is placed on the DFm as it informs on the spatial distribution and is less susceptible to the room shape (Mardaljevic et al., 2013). However, it is important to note that, while the DF remains widely utilized, it is regarded as outdated, as elaborated in 2.1. Daylight. Alternative climate-based metrics could have also been considered for setting the minimum threshold.

Description of the systems

Characteristics of the system

Outlining the technical aspects and key information of the system is crucial for understanding the focus of the environmental evaluation. This information can be grouped into three categories: characteristics of the daylighting system, characteristics of the study room, and characteristics of the geographical context.

Within these groups, these are some of the specific aspects to outline:

- **Daylighting system size**: All relevant dimensions to represent the system and its spatial relationship with the room.
- **Daylighting system material characteristics**: Including density, thermal conductivity, thickness, specific heat, and any other necessary attributes to evaluate their thermal, optical, and physical properties.
- **Visual transmission**: For both the transparent elements and the whole system, e.g., including shading.
- **Solar Heat Gain Coefficient (g-value):** The value of the whole system.
- **Room Dimensions**: All relevant dimensions allowing a precise representation of the room.
- **Materials of the Room Elements**: Detailed description of the physical characteristics of each room element, including material composition, physical characteristics, and reflectance of each surface.
- **Orientation**: Exact orientation of the wall in which the daylighting system is installed, measured in degrees (°), being north at 0°, east at 90°, south at 180°, and west at 270°.
- **Geographical location**: Specific coordinates detailing the location of the room.

Description of the baseline daylighting system

The baseline system represents the characteristics of an average window in Europe. According to a report elaborated by Eurac Research (European Commission, 2018), the average window in the EU building stock presents a U-value of 3.4 W/m²K, as the most common windows in the EU and in the UK are still low-performing glass, either uncoated double-glazed windows or single glazed.

The baseline comprises an aluminium-framed window with a double-glazed, uncoated glazing unit. The glazing data was retrieved from the EPD of *Climalit* double-glazing unit from Saint-Gobain Glass (Saint-Gobain Glass FRANCE, 2022). This EPD describes a double-glazed unit without low-e coating and a glass U-value (Ug) of 2.6 W/m²K while the frame characteristics, generic values for a metallic frame with thermal brake were considered from the ISO 10077-1 (International Organization for Standardization, 2017a). This result in an overall window U-value of 3.1 W/m²K.

Table 13 includes a summary of the physical, visual, and thermal properties characterising the conventional system.

Table 13: Physical, visual, and thermal properties of the baseline system.

Property	**Value**	**Source**
Physical Characteristics		
Frame Surface	20%	
Divisions	Single light	
Visual Properties		
Visual Light Transmittance (T_{vis})	0.830	(Saint-Gobain Glass FRANCE, 2022)
Glass reflectance, exterior ($R_{vis,exterior}$)	0.150	(Saint-Gobain Glass FRANCE, 2022)
Glass reflectance, interior ($R_{vis,interior}$)	0.150	(Saint-Gobain Glass FRANCE, 2022)
Frame roughness	0.100	(Design for Climate & Comfort Lab, 2021a)
Frame reflectance, total ($R_{vis,total}$)	0.433	(Design for Climate & Comfort Lab, 2021a)
Frame reflectance, diffuse ($R_{vis,diff}$)	0.404	(Design for Climate & Comfort Lab, 2021a)
Frame reflectance, specular ($R_{vis,spec}$)	0.030	(Design for Climate & Comfort Lab, 2021a)
Thermal Properties		
U-value, glass (U_g)	2.6 W/m²K	(Saint-Gobain Glass FRANCE, 2022)
U-value, frame (U_f)	3.8 W/m²K	(International Organization for Standardization, 2017a)
U-value, total (U_w)	3.1 W/m²K	(International Organization for Standardization, 2017a)
g-value, glass	0.8	(Saint-Gobain Glass FRANCE, 2022)

3.2 Life-Cycle Inventory (LCI)

3.2.1 Type of data

The inventory of an LCA for a daylight system should as well be in line with the goal and the scope. The type of data should include information about the materials used, energy consumption, energy source scenario, transportation, and waste generated throughout the life cycle of the system. This methodology prioritizes data collection during the use phase, including both foreground and background data and adhering to the defined system boundaries.

Foreground data involves information obtained directly from the main process system, such as technology-focused data provided by developers, manufacturers, and companies involved, collected through questionnaires or forms. Special attention should be paid to the energy consumption data during the use phase, which can be obtained through in situ monitoring or with the help of specialised simulation software.

On the other hand, background data includes commercial materials and components, which can be obtained from technical sheets, specific EPDs, Product Environmental Footprint Reports (PEFRs), or other relevant references that are geographically relevant. This also refers to data for the upstream and downstream processes, where the inventory can be based on recognized datasets that are suitable for LCA modelling. Where such data is not available, average data or, alternatively, generic data can be considered. Regardless of the data source, transparency in reporting the data source is crucial.

3.2.2 Data quality requirements

The quality of the data used in the inventory for a daylight system must adhere to the requirements of EN 15804. When alternative data sources are used, this proposed harmonised methodology proposed the utilisation of the Data Quality Index within the Level(s) Framework in order to study the quality of the used data. This index serves as a tool to assess the quality of the data and determine the data acceptance thresholds, guaranteeing accurate and reliable information throughout the assessment process.

3.2.3 Allocation procedures for recycling

Allocation may be necessary when materials are reused or recycled in other products when assessing a daylight system, such as specified in ISO14040/44:2006. Additionally, recycling plays a significant role in reducing the environmental impacts of the system. For addressing the burdens, or avoided burdens, associated with materials or products during the building's use phase, the recommended approach is the 0:100 model. In this model, the credits for recycling products are assigned to the producer of the recycled material, meaning that the recycled product gets credits for avoiding future emissions through the substitution of virgin materials (Corona et al., 2019). Consequently, it is recommended in this methodology to consider that the products entering the system are made from virgin materials while the products leaving the system are recycled. In case allocation needs to be considered, the system boundaries of the LCA can be effectively addressed following a similar approach as specified in ISO 14040:44 and summarized in

Table 9. If any other approach is to be used, this must be clearly justified.

3.2.4 Cut-off criteria

Following the ISO 14040/44:2006, it is acknowledged the need for cut-off in the assessments. Following what is established in the Product Environmental Footprint, this methodology establishes that any processes and flows excluded cannot account for more than 3% of the material or energy flow.

3.2.5 Simulation parameters

Daylight simulations

This methodology advises to adhere to the guidelines articulated in the European standard EN17037 when conducting daylight simulations. Table 14 specifies the recommended parameters to use in daylighting simulations, including the recommended radiance parameters for good practice (Kharvari, 2020). Any deviation from these values must be reported.

Table 14: Recommended values for the daylight simulations parameters.

Parameter	Value
Work plane Height	0.85 m
Sensor Spacing	0.50 m
Target Inset	0.60 m
Minimum Inset	0.50 m
Occupancy Schedule	8 am to 4 pm with DST
Ground plane extension	20.0 m
Ambient bounces	24
Ambient accuracy	0.1
Ambient resolution	128
Ambient divisions	4096
Ambient super-samples	1024

Energy simulations

Project and geography specific data are prioritized regarding the settings necessary to perform the energy simulations. In the absence of this type of data, generic data can be used, trying to make it the most project and context relevant possible.

Regarding the room's constructions, in the absence of specific values, the report "European Building Stock Analysis" published by Eurac Research is a reliable source to select default constructions in a European context (Gevorgian et al., 2021). Other sources can be used if they are project relevant.

If no other relevant systems can be specified, it is possible to consider the ASHRAE 90.1-2019 default constructions, or zone settings. However, it is important to understand this standard is based on American definitions, so they might not be applicable or accurate to every context. The selection of these values should align with the most appropriate room type and climate zone.

Table 25 and Table 26 in section Error! Reference source not found.. Error! Reference source not found. provide two examples of the necessary parameters to be specified for each assessment.

The choice of the weather data must be pondered. This methodology recommends the use of Typical Meteorological Year (TMY) weather data files, because of its accuracy to represent historic data and wide availability (Chakraborty et al., 2016). In addition, the inclusion of future data can be studied, obtained from a reliable source, considering the performance of a sensitivity analysis comparing different weather data type. Nevertheless, the weather file selected must be reported clearly in the LCI section of the assessment.

3.3 Life-Cycle Impact Assessment (LCIA)

3.3.1 Environmental impact categories

For this methodology, the impacts are reported for the climate change category, measured by the GWP 100 years indicator in kgCO_2-eq. GWP is defined as "the ratio of the amount of heat trapped by 1 kg of gas during 100 years to the amount of heat trapped by the same mass of CO_2 during the same period" (Van Nieuwenhuyse et al., 2023).

GWP remains a major indicator of LCA (Knauf, 2015), with its importance relying on the alignment of international institutions to combat climate change, such as the Paris Agreement, where the importance of reducing GHG emissions is highlighted (UNFCCC, 2015). Following this, governments all around the world are committed to this reduction, using regulations and emission limits.

Within this context, GWP100 serves as a critical metric, assessing the impact over a 100-year period, and aligning with the Kyoto protocol and the international guidelines (UNFCCC, 2023). The unit of measure for this impact is kgCO_2-eq.

3.3.2 Characterisation model

As mentioned, the environmental impact to be considered is the GWP100 and the characterisation factors to consider must be those included in the latest Intergovernmental Panel on Climate Change (IPCC) Assessment Report, being the Sixth Assessment Report (AR6), published in 2021 (IPCC, 2021), at the moment of publishing this document.

3.4 Life-Cycle Interpretation (LCI)

3.4.1 Analysis of the results

A thorough examination of environmental impacts across each life cycle stage is crucial. Addressing how decisions made in one aspect may affect others is essential for comprehending the interrelations of different facets within the system. This method seeks to understand the driving forces behind the outcomes, facilitating this holistic comprehension and unveiling potential improvements with an environmental focus. For that, results regarding the following four aspects must be clearly reported for a robust analysis.

Daylight provision results

As mentioned in the FU, the DFm is used as the minimum benchmarking values to be met in order to consider the system to provide an adequate daylight quality inside the space and it should be therefore reported for both the novel system and the baseline. In addition, other metrics can be reported such as the ADF, targeted UDI, DA, or the ASE, enhancing the understanding of the daylight performance. However, no minimum threshold values are set for these other metrics.

Indoor comfort results

To consider the impact of daylighting system characteristics on indoor comfort, the methodology incorporates the assessment of overheating hours. To define the concept of "overheating", this framework adopts the recommendations from the Forum for Energy-Efficient Buildings from Sweden (FEBY). Accordingly, the report must explicitly present the number of hours exceeding 26°C between April and September for the baseline and the novel systems assessed (Forum för Energieffektivt Byggande, 2019).

Energy performance results

It is imperative to understand the energy performance of the studied space for assessing the system's, especially considering the 50-year period established in the FU and the necessity to report the results based on energy performance. Therefore, the results for both the baseline and the novel system must be reported in the form of Energy Use Intensity (EUI) of the study room, using kWh/m²/year as the unit. If available, the breakdown of the EUI by sources can be reported as well to increase the understanding of the performance.

GWP results

The environmental impact must be presented based on the GWP, in a clear form. Table 15, presented below, provides a template for the presentation of these results. This table must report the absolute GWP values for each of the modules included in the system boundaries of the assessment, for both the novel system assessed and the baseline.

Table 15: Suggested table template for the presentation of the GWP results.

Section	**Category**	**Baseline GWP ($kgCO_2$-eq)**	**Novel system GWP ($kgCO_2$-eq)**
A1	Raw material supply		
A2	Transport		
A3	Manufacturing		
A4	Transport		
A5	Construction Process		
B1	Use phase		
B2	Maintenance		
B3	Repair		
B4	Replacement		
B5	Refurbishment		
B6	Energy consumption		
B7	Water use		
C1	Deconstruction		
C2	Transport		
C3	Waster Processing		
C4	Disposal		
D	Reuse/Recovery/Recycle		
Total			

Additionally, this methodology highly recommends creating a graph to display the difference in performance between the baseline and the assessed system. Figure 8 shows a suggested graph in which the baseline performance represents the benchmark value, while the variation on the performance is displayed by the bars. They represent an improvement in the performance compared to the baseline when the results are negative, or a worsening, when the values are positive.

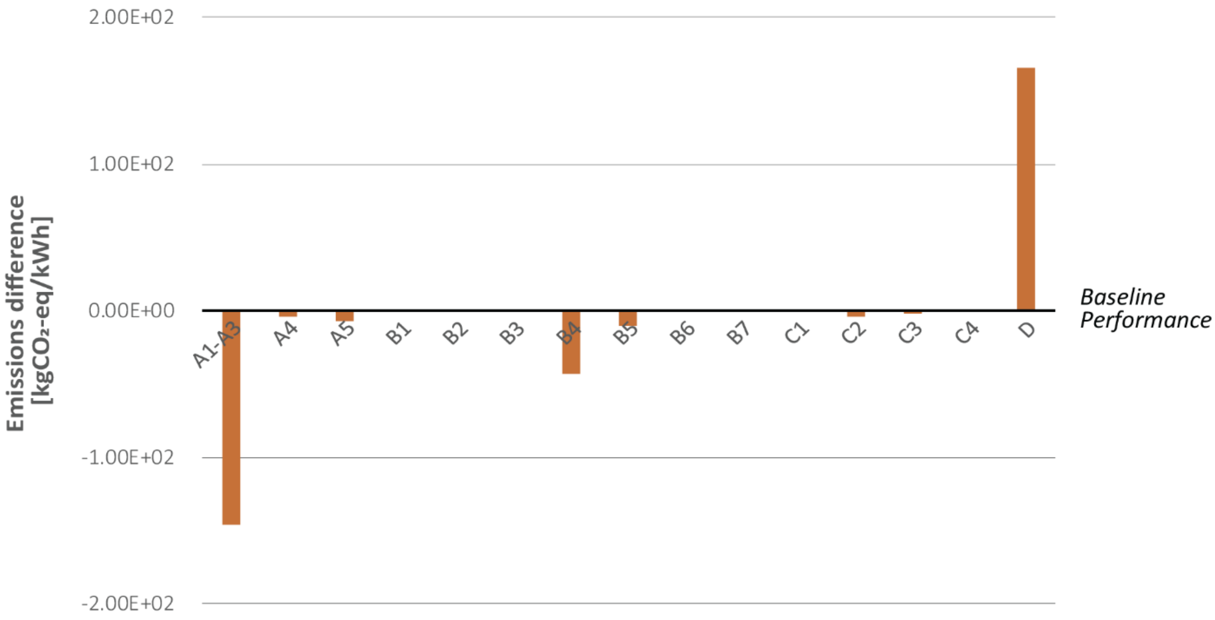

Figure 8: Suggested graph template for the presentation of the GWP results.

3.4.2 Aggregation method

The assessment focuses on a singular environmental impact category. Consequently, there is no need for the application of weighting or normalising factors. To maintain consistency and comparability across assessments, all the results are systematically normalized by the FU, as detailed previously.

3.4.3 Uncertainty and sensitivity analysis

Following the guidelines outlined in ISO 14040 and 14044, conducting a sensitivity analysis is recommended, particularly when assessments are intended for comparative purpose. They increase the robustness and accuracy of the results, providing valuable insights regarding which factors have the most influence.

The first step involves identifying relevant or variables that are expected to have an impact on the outcomes. These may include input parameters, inventory, assumptions, model coefficients, or external factors. It is important to document and justify the selection of these features to ensure transparency and reproducibility of the analysis.

It is noteworthy that, while this recommendation is clear, there are no specific characteristics indicated for mandatory testing, as these may vary depending on the specific context of the assessment. This flexibility allows for practitioners to adapt them to the specific goals of their assessments.

Similarly, the approach to follow is also flexible. This framework suggests the use of a Monte Carlo simulation, which involves randomly sampling values from probability distributions assigned to each feature and providing a probabilistic assessment of the sensitivity, allowing for a more robust analysis. However, alternative methods, such as the one-at-a-time approach or Design of Experiments, are allowed as well.

4 Harmonised methodology application

Hereunder, the harmonised methodology described in the previous section is applied to two different scenarios, following the same structure. First, the Goal and Scope sections, including a description of the systems assessed, with details of the daylighting system, the study rooms, and the geographical context. This is followed by a detailed LCI, leading to the LCIA, and concluding with the presentation of the LCI.

4.1 Goal and Scope

4.1.1. Goal

This study aims to assess the environmental impact of a novel daylighting system compared to a standard window in two distinct spatial contexts. The baseline system represents the average window found in the EU building stock, while the innovative solution is an electrochromic glazing unit window. The two different contexts emulate firstly a single office space (PASSYS test cell), and secondly an open plan office (BESTEST test cell). Figure 9 provides a visual representation of both scenarios.

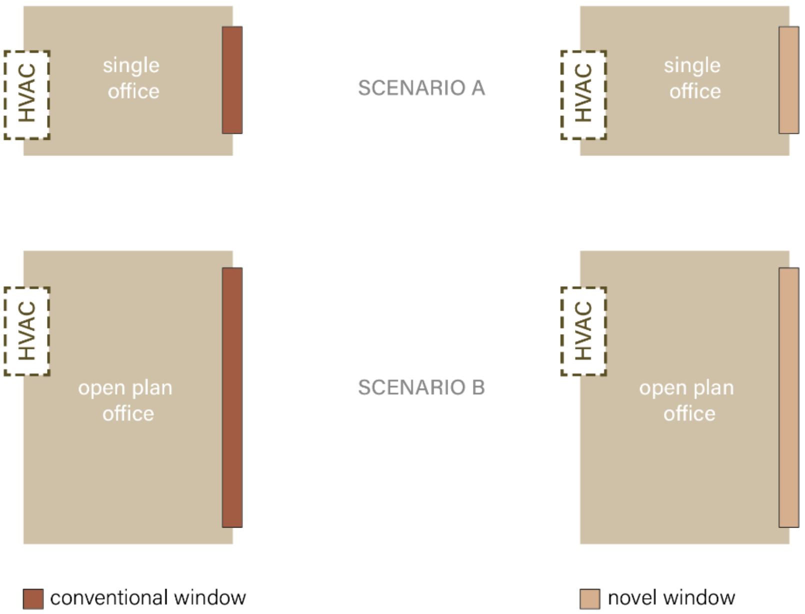

Figure 9: Scenarios considered in the assessment: Scenario A, a single office space (PASSYS); and Scenario B, an open plan office (BESTEST)

The assessment is set within the context of building renovation. Therefore, by comparing a conventional system with a novel approach, this helps to identify the environmental benefits of adopting modern daylighting technologies, providing a scheme to explore the environmental impacts across the building's lifetime.

To make the scenarios comparable, geometry, geographical context, orientation, energy source scenarios, and any other input that might affect the comparability of the results are kept consistent. The difference lies in the daylighting system, which is adjusted to match the daylight performance of the baseline system by adjusting the size. The size of the daylight systems is determined iteratively by their daylight performance, for both the baseline and the novel system, until the systems reach the minimum threshold for DFm, established in section **0. Daylight provision results**.

4.1.2. Scope

System boundaries

Because of data limitations, the application of the methodology focuses solely on the manufacturing and use phase of the system, including modules A1 to A3, B4 and B6, in line with the system boundaries outlined in EN15978. Consequently, considerations regarding the inventory and any impact related to the decommissioning and the end-of-life are not considered.

The scope includes the environmental impacts derived from replacement activities within the use phase (B4), including raw material extraction and energy for sustainment, as detailed in Figure 10. However, data concerning to these activities is limited, hence the segmented boxes.

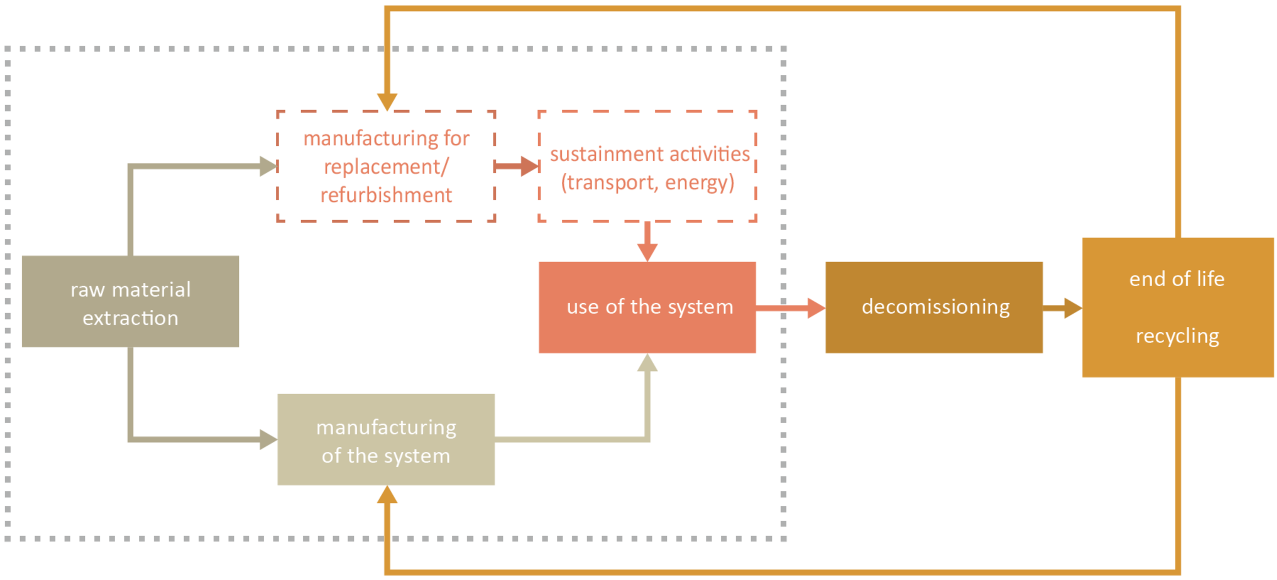

Figure 10: Overview of the flows involved in the LCA, highlighting those included in this assessment.

Functional Unit (FU)

The results of the assessment will be reported and referred to the FU. As outlined in the standardized methodology described earlier, the focus is on the efficiency of each system in terms of energy consumption, it may be more suitable to compare the CO_2 equivalent emissions per unit of energy. Therefore, the environmental impacts are reported per "kWh of primary energy consumption difference compared to a baseline in a space with a minimum DFm of 1% over a 50-year period", which is the FU defined in this study. In both evaluations, the innovative solution and baseline in the scenarios defined will be made using the same mentioned FU over the period detailed, keeping the same daylight performance for a consistent comparative approach.

Description of the system

Characteristics of the daylighting system

For the innovative daylighting system assessment, the objective is to analyse a highly insulated and non-conventional daylighting system, testing its performance in contrast to the baseline solution previously described.

The novel system is represented by a high-performing window, with an electrochromic (EC) insulation glass unit. EC glazing essentially acts like a window with adjustable tint, allowing for better control of heat and glare. This is caused by the five-layer coating, which can change in optical properties, also called state, when an external electric voltage is applied. These reactions are typically triggered by the amount of solar radiation the glass receives (Casini, 2018) and the added energy consumption is very low, with an average of 0.05 W/m² (Finnglass Oy, 2020).

The window consists of a triple-glazed EC glazing unit with a low-e coating, housed in an aluminium frame with PVC-U frame and spacer bars for improved thermal performance (total U-value: 1.2 W/m²K). Information for the IGU was obtained from the EPD of a triple-glazed EC glazing unit from Saint-Gobain SageGlass [68], while framing properties are based on ISO 10077-1 [53].

The window consists of a triple-glazed EC glazing unit with a low-e coating and an aluminium frame. Information for the IGU is obtained from the EPD of the triple-glazed EC glazing unit from Saint-Gobain SageGlass (SAGE Electrochromics Inc-Saint Gobain, 2020), while the framing properties are extracted from the ISO 10077-1 (International Organization for Standardization, 2017a), considering a PVC-U frame and glazing spacer bars with improved thermal performance were considered. The total window U-value is 1.2 W/m²K. Table 16, shown below, includes the properties describing the novel system.

Table 16: Visual and thermal properties of the novel daylight system.

Property	**Value**	**Source**
Physical Characteristics		
Frame Surface	20%	
Divisions	Single light	
Visual Properties		
Visual Light Transmittance (T_{vis})	Variable (see Table 17)	(SAGE Electrochromics Inc-Saint Gobain, 2020)
Glass reflectance, exterior ($R_{vis,exterior}$)	Variable (see Table 17)	(SAGE Electrochromics Inc-Saint Gobain, 2020)
Glass reflectance, interior ($R_{vis,interior}$)	Variable (see Table 17)	(SAGE Electrochromics Inc-Saint Gobain, 2020)
Frame roughness	0.10	(Design for Climate & Comfort Lab, 2021b)
Frame reflectance, total ($R_{vis,total}$)	0.845	(Design for Climate & Comfort Lab, 2021b)
Frame reflectance, diffuse ($R_{vis,diff}$)	0.817	(Design for Climate & Comfort Lab, 2021b))
Frame reflectance, specular ($R_{vis,spec}$)	0.029	(Design for Climate & Comfort Lab, 2021b))
Thermal Properties		
U-value, glass (U_g)	0.6 W/m²K	(SAGE Electrochromics Inc-Saint Gobain, 2020))
U-value, frame (U_f)	2.0 W/m²K	(International Organization for Standardization, 2017a))
U-value, total (U_w)	1.0 W/m²K	(International Organization for Standardization, 2017a))
g-value, glass	Variable (see Table 17)	(SAGE Electrochromics Inc-Saint Gobain, 2020))

As mentioned, EC glazing's properties dynamically change depending on the amount of the solar radiation hitting in the window.

Table 17 includes a breakdown of the main visual properties of the glass, considering four different states.

Table 17: EC glazing unit performance data (SAGE Electrochromics Inc-Saint Gobain, 2020).

State	**Visual Light Transmittance (Tvis)**	**Exterior reflectance ($R_{vis,exterior}$)**	**Interior reflectance ($R_{vis,interior}$)**	**Solar transmission**	**g-value**
Clear State	0.54	0.19	0.20	0.340	0.36

Intermediate State 1	0.16	0.10	0.16	0.080	0.09
Intermediate State 2	0.05	0.10	0.16	0.020	0.05
Fully Tinted	0.01	0.11	0.16	0.004	0.03

Characteristics of the study room

Scenario A: PASSYS study cell

PASSYS project was initiated in 1986 by the Commission of the European Communities, being the primary focus increasing the confidence in passive solar heating systems by validating building energy simulation programmes. The collaborative efforts of around 60 researchers lead to develop specialised test cells for developing reliable test procedures, in various European locations (Jensen, 1995)).

The main characteristics of the cells developed were their “hard casing” concept, featuring a steel frame filled with mineral wool, a two-zone internal structure, with a service room and a test room divided by an insulated wall and a connecting door and, finally, a South wall designed to accommodate different components and offering a controlled indoor environment. The dimensions of the PASSYS test room are detailed in Table 18 and Figure 11.

Table 18: Interior and exterior dimensions of the PASSYS test room.

	Length (m)	Width (m)	Height (m)
Outside overall	8.44	3.80	3.61
Test room inside	5.00	2.76	2.75
Service room inside	2.40	3.58	3.29

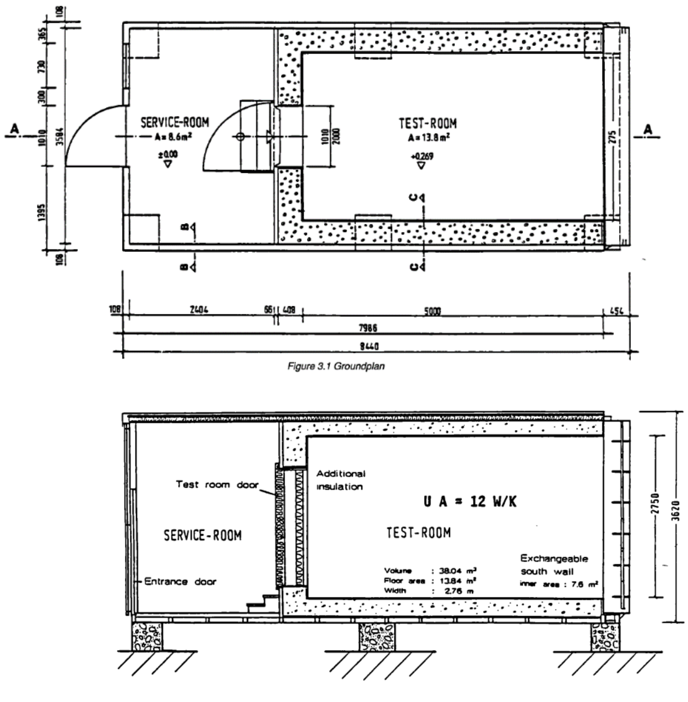

Figure 11: Floor plan and longitudinal section of the PASSYS test cell, from the PASSYS project report (European Commission, 1990).

Scenario B: BESTEST study cell

This project was a collaborative work led by the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Programme Task 12. It was originally developed in the late 80s and early 90s and officially published in 1995.

The dimensions are mostly consistent across all cases proposed in BESTEST: a single rectangular zone measuring 6 m x 8 m with a 2.7 m floor-to-ceiling height and no partitions, as the interior dimensions. In addition, the project includes representation of both lightweight and heavyweight buildings. For this assessment, BESTEST Case 600 was selected. This case represents a low mass case with South-oriented windows and no overhang. Figure 12 presents a schematic of the BESTEST Case 600 room, including its key dimensions.

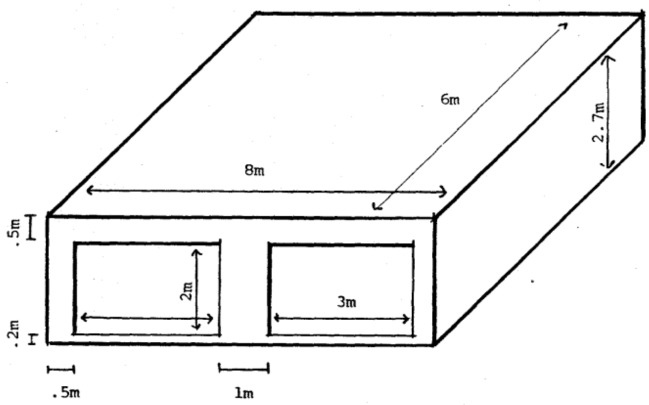

Figure 12: Axonometric projection of the BESTEST Case 600 room, from the BESTEST project report (Judkoff & Neymark, 1995).

Geographical location

The location for the room considered in the assessment is Lund, Sweden, placed completely unobstructed on a flat surface. The wall on which the windows are placed is facing South (180°, with Noth at 0°). This location corresponds to the climate zone 5A in the ASHRAE standards (ASHRAE, 2021)).

4.2 Life-Cycle Inventory (LCI)

4.2.1. Foreground data

Bill of materials

The material weight is determined based on the WWR used in each scenario, assuming a fixed glass area of 80%. In Scenario A, the size established for the baseline system represents a 20% WWR (1.03m x 1.48m), while for the novel system increases up to a 29% WWR (1.49m x 1.48m). In Scenario B, the baseline is set at 21% WWR (3.06m x 1.48m) and the novel system at 28% WWR (4.09 x 1.48m). In both scenarios, the windows are placed at a windowsill height of 0.90 m and feature an 8 cm thick frame.

These dimensions are then combined with the information provided by the EPDs. In the conventional glazing unit, the data is sourced from the Saint-Gobain Double Glazing Climalit EPD (Saint-Gobain Glass FRANCE, 2022)), while for the novel system, it comes from the SageGlass EPD (SAGE Electrochromics Inc-Saint Gobain, 2020)). Frame data is extracted from the German database "Ökobaudat". The aluminium frame is based on the process data set named "Aluminium frame profile, powder coated", and the PVC frame on "Window frame PVC-U" (Sphera Solutions GmbH, 2018, 2022)).

Table 19 and Table 20 provide a breakdown of the bill of materials for each scenario.

Table 19: Bill of materials for the baseline system, considering both scenarios.

Element	Weight (kg)	
	Scenario A	Scenario B
Glazing unit	23.66	70.29
Butyl sealant	0.02	0.07
Sealant	0.24	0.72
Space Bar	0.24	0.72
Desiccant	0.24	0.72
Fill gas (air)	0.02	0.07
PVB Interlayer	0.05	0.14
Aluminium Frame	5.12	9.26
Total Weight	29.61	82.01

Table 20: Bill of materials for the novel system, considering both scenarios.

Element	Weight (kg)	
	Scenario A	Scenario B
Float Glass	101.62	278.94
Device Glass	9.71	26.64
Coating	0.11	0.31
Space Bar	1.14	3.13
Desiccant	1.14	3.13
Fill gas	0.11	0.31
PVB Interlayer	0.23	0.63
Wiring Components	0.11	0.31
PVC-U Frame	16.63	31.19
Total Weight	129.21	340.29

The replacement scenario focuses on partial replacements, considering the individual replacement of frame and glass individually, once their lifespan. To simplify calculations, periodic maintenance and repairs are not considered. The reported lifespans of the components are used instead, resulting in 0 impact for modules B2 and B3 and an underestimation of the lifespan of the products.

Data source for the RLP varies. Some of the aforementioned EPDs provide this information, as it is the case of the Double Glazing Climalit EPD with a 30-year lifespan. In other cases, other sources need to be used, as for the 20-year lifespan of the EC glazing, which is based on previous research (Nundy et al., 2021)). Similarly, frames lifespans are assumed to be 25 years and 20 years for the aluminium and the PVC-U, respectively (Carlisle & Friedlander, 2016)).

Considering these factors over the 50-year reference period, the conventional glass and the aluminium framing are replaced once at year 30 and 25 respectively, while the EC glazing and the PVC-U frame undergo two replacements, at year 20 and year 40.

Energy source scenario

Several assumptions are considered for the energy source. First, disregarding any degradation, improvement in the envelope, or replacement of HVAC systems, the EUI of the room is deemed constant throughout the 50-year timeframe of the assessment in order to simplify the calculations. This means that any degradation, improvement in the envelope, or replacement of the HVAC systems is disregarded. Similarly, the EUI is assumed to be covered by electricity provided by the local electricity grid.

To account for the environmental impact of electricity consumption, a Carbon Intensity (CI) value needs to be defined to find the appropriate conversion factor between energy consumption and GHG emissions. Given the substantial variation in CI values across countries and regions, the European grid CI is assumed for this assessment, based on the interconnected nature of the European electricity system (Dokka et al., 2013)).

The basis of the CI is research that developed five future scenarios, depicting potential developments in the power system in Europe until 2050 (Graabak & Feilberg, 2011)). These scenarios were later extrapolated in order to predict and create a linear graph showing the projected confidence interval for the European grid, under the assumption that it will be fully decarbonised by 2055, as shown in Figure 13.

Although the research itself dates back 15 years, the extrapolation remains valid, as evidenced by the close match between the estimated CI for 2020 (280 gCO_2-eq/kWh) and the actual value (271 gCO_2-eq/kWh) (Our World In Data, 2022)). Consequently, over a 50-year period, the yearly average CI is 79.36 gCO_2-eq/kWh.

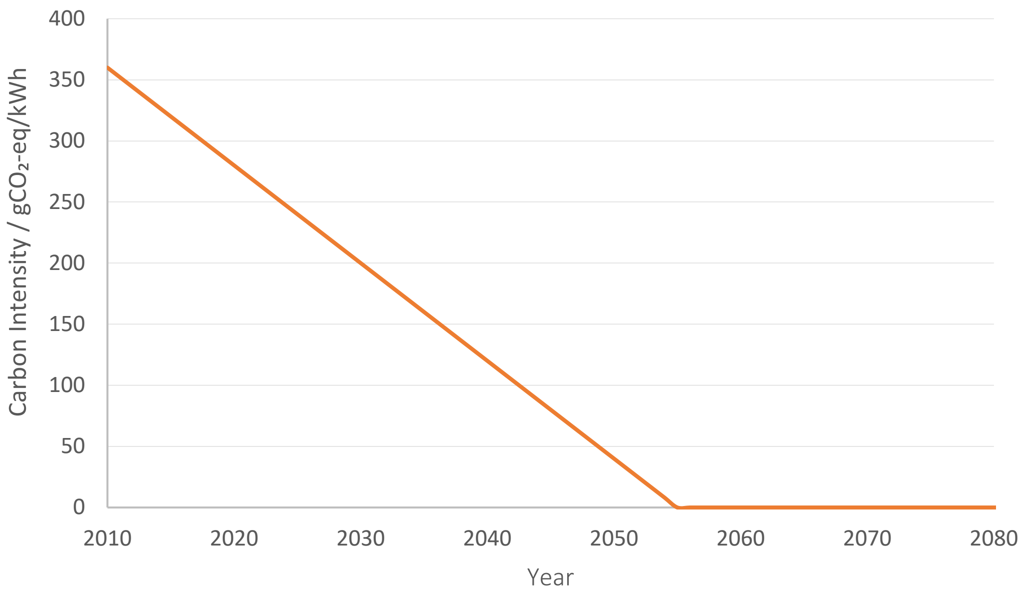

Figure 13: Projected evolution of the CI of the electricity in Europe from 2010 to 2055 (Dokka et al., 2013))

Other LCA calculation parameters

For the calculation of the embodied impacts of the system, the LCA was performed in the specialised software OneClickLCA. In this software, to account for the transportation impacts of the material replacement, the transport considered for each product was 50 km, with a trailer of 40 tonnes capacity and a filled rate of 100%. Empty return trips are excluded.

Furthermore, in the manufacturing process of the products, as the energy profiles adhere to the specifications provided in the EPDs, no conversion factors were applied to align with the conditions in the assessment country.

OneClickLCA currently lacks the functionality to specify the electricity grid CI. Therefore, the operational impacts are manually calculated after exporting the embodied impacts from the specialised software.

4.2.2. Background Data

Data Quality and Datasets

The harmonised methodology establishes in section **3.2.2. Data quality requirements** that the used data must adhere to the EN 15804 requirements or employ the Data Quality Index as an alternative. As detailed in

Table 21, all data employed in this assessment, whether product specific or generic, complies with the EN 15804 standards and can be consequently deemed acceptable.

Table 21: Data sources and quality compliance.

Product	Data Type	Validity	Declared Compliance	Source
Double Glazing Climalit	Product Specific	2027	ISO 14025 EN 15804:2012+A2:2019	(Saint-Gobain Glass FRANCE, 2022))
SageGlass EC Glazing	Product Specific	2025	ISO 14025 ISO 2193:2007 EN 15804	(SAGE Electrochromics Inc-Saint Gobain, 2020))
Aluminium frame profile	Generic	2024	EN 15804:2012+A2:2019	(Sphera Solutions GmbH, 2022))
Window frame PVC-U	Generic	2024	EN 15804:2012+A2:2019	(Sphera Solutions GmbH, 2018))

4.2.3 Allocation procedures and recycling

Because of the particular conditions of this assessment, the suggested 0:100 approach for recycling credits mentioned in section **0.**

Allocation procedures for recycling, cannot be considered as the End-of-Life phase is not part of the scope. For this reason, this assessment follows the 100:0 approach, considering that the materials entering the system in the replacement, repurposing, and repair activities can contain recycled materials and these credits can be considered in the respective modules.

4.2.4 Simulation parameters

The analysis is conducted using historic weather data, relevant to the geographical location of the assessment, obtained from "Climate.OneBuilding.Org". The file includes data from the period 2007-2021, and it is named SWE_SN_Lund.Sol.026330_TMYx.2007-2021.

Daylight simulations

Error! Reference source not found. outlines the reflectance values used for each surface in the room. They are based on the IES LM83-12 materials (IES Illuminating Engineering Society of North America, 2012)), and they align with the recommendations from the EN 17037. The room was considered completely empty of furniture, with a ground reflectance of 20%.

Table 22: Reflectance considered for each surface in the simulation.

Building Element	ClimateStudio Material Name	Reflectance
External Ground	Floor LM83	0.20
Interior Floor	Floor LM83	0.20
Interior Walls	Wall LM83	0.50
Ceiling	Ceiling LM83	0.70

The baseline system considers the default ClimateStudio glazing "Starphire–Starphire", which essentially has the same properties as the glazing detailed in section **0. Description of the baseline daylighting system.**

For the novel system assessed, the default ClimateStudio "sage" dynamic window is considered. However, it is important to note that this glazing unit does exactly replicate the characteristics of the novel system previously described. **Error! Reference source not found.** highlights the performance differences, observing that the ClimateStudio default glazing presents higher T_{vis} in its three clearer states. These differences will lead to an overestimation of the daylighting results, but they are deemed negligible enough to consider the calculations meaningful.

Table 23: Comparison of Sage Glass' Visual Light Transmittance reported in the EPD and ClimateStudio.

State	EPD Reported T_{vis}	ClimateStudio T_{vis}
Clear State	0.540	0.597
Intermediate State 1	0.160	0.173
Intermediate State 2	0.050	0.055
Fully Tinted	0.010	0.009

The tint schedule considered for this glazing is the default by ClimateStudio, namely "LEEDv4 2% Rule". As defined by ClimateStudio (Solemma LLC, 2020)), this rule stipulates that "for each hour of the year, if more than 2% of the occupied area receives direct sunlight (defined as more than 1000 lux directly from the solar disc), […] the transmittance of the glass is lowered until either the sensors are brought below 1000 lux, or the glass is in its darkest tint state".

Lastly, the simulation parameters considered align with those specified in Table 14 in section **3.2.5. Simulation parameters**. However, for the radiance parameters, ClimateStudio only allows adjustments to the "Samples per sensor". Therefore, the simulation is performed considering the default radiance parameters from ClimateStudio and 4096 "samples per sensor".

Scenario A
The simulations are based on a Rhino model created based on the information extracted from the PASSYS documentation displayed in Figure 14. The surfaces around the window represent the 300 mm thickness of

the walls, with the window places exactly at 150 mm from the exterior. They are performed using the software ClimateStudio in Grasshopper.

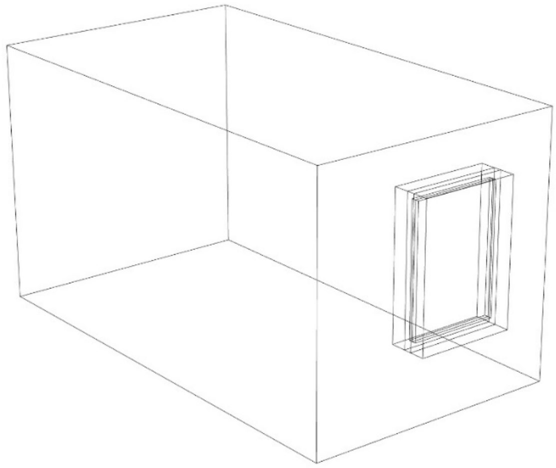

Figure 14: *Daylight model used for the simulations in ClimateStudio in Scenario A.*

Scenario B
The simulation for this scenario is performed on the model displayed in Figure 15. Similar to the previous scenario, the windows are placed at 150 mm from the interior surface and the simulations are run using Grasshopper and ClimateStudio.

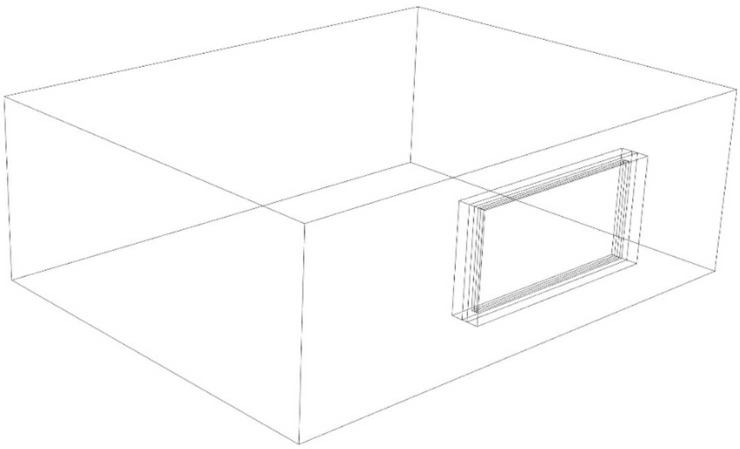

Figure 15: *Daylight model used for the simulations in ClimateStudio in Scenario B.*

Energy simulations

Motivated by the goal of assessing a renovation context, the actual U-values of the study rooms room are intentionally not considered, as the low values of the PASSYS and BESTEST rooms do not accurately represent a building in need of renovation.

For this reason, a new set of constructions is considered for the energy simulation. These new U-values are based on the European Commission report detailing the European building stock (European Commission, 2018)) and can be found in Table 24. They are the result of a weighted average of the European Union and United Kingdom U-values for both residential and service buildings. As per this report, these U-values correspond to a residential building from the 1970s or a service building constructed before 1945.

Table 24: *U-values and thermal capacitance considered in the energy simulations.*

Component	EU+UK Average U-values (W/m²/K)	Thermal Capacitance (kJ/K/m²)

Wall	1.22	687.780
Roof	1.06	688.725
Floor	1.02	788.725

To account for the thermal capacitance of these components, specific construction materials are selected, reflecting the most common practices in Europe for service buildings. Concrete, often coupled with insulation, is selected for walls, roofs, and floors. The breakdown of the elements considered, and their thermal properties, can be found in Table 31 in **Annex A. Materials characteristics.**

Scenario A

Figure 16 depicts the energy model, which is based on the Rhino geometry of the cell room, where the surfaces represent the interior space. The South-facing wall contains the window, including the surfaces representing the 300 mm thickness of the outer wall. The window is modelled as a single surface, detailing the frame characteristics in the appropriate ClimateStudio component.

Furthermore, the simulations exclude the service room. The dividing wall separating both spaces is considered adiabatic, with the same construction as the external walls and omitting the door separating both spaces. Lastly, the floor is considered exterior as the room is elevated approximately 800 mm from the ground.

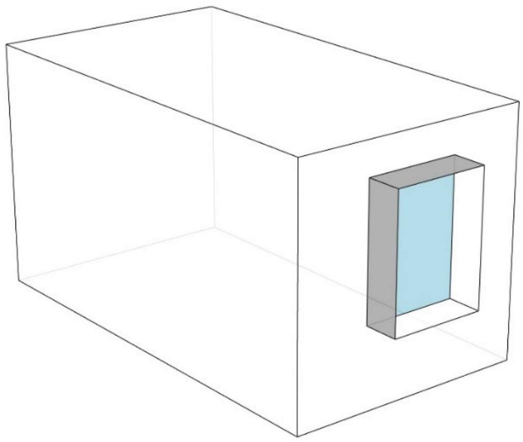

Figure 16: *Energy model used for the simulations in ClimateStudio in Scenario A.*

The zone settings used in the assessment are those specified in **Error! Reference source not found.**. Most of these values are selected from the ClimateStudio zone template 90.1-2019 SmallOffice – ClosedOffize CZ 5, based on the ASHRAE standard and adapted to the room type and Lund's climate zone. A detailed breakdown of the schedules considered is given in Table 32 and Table 33 in **Annex B. Simulation parameters**.

Table 25: *Zone settings considered in Scenario A, based on ASHRAE 90.1* (ASHRAE, 2019))

Settings	**Value**
People density	0.05 p/m²
Metabolic rate	1.2 met
Occupancy Schedule	OfficeSmall BLDG_OCC_SCH
Equipment Load	9.36 W/m²
Equipment Availability Schedule	OfficeSmall BLDG_EQUIP_SCH_2013
Lighting Power Density	7.97 W/m²
Illuminance Targe	500 lux
Lights Availability Schedule	OfficeSmall BLDG_LIGHT_SCH_2013
Dimming Type	Off
Heating Setpoint	Based on OfficeSmall HTGSETP_SCH_NO_OPTIMUM

Max Heat Supply Air Temperature	30 °C
Heating COP	3.50
Max Heating Capacity	100 W/m²
Max Heat Flow	100 m³/s/m²
Cooling Setpoint	Based on OfficeSmall CLGSETP_SCH_NO_OPTIMUM
Min Cool Supply Air Temperature	18 °C
Cooling COP	3.50
Cooling & Heating Limit Type	No Limit
Max Cooling Capacity	100 W/m²
Max Cool Flow	100 m³/s/m²
Min Fresh Air Per Person	2.36 l/s/p
Min Fresh Air Per Area	0.30 l/s/m²
Heat Recovery Type	Enthalpy
Heat Recovery Efficiency Sensible	0.80
Heat Recovery Efficiency Latent	0.80
Infiltration Calculation Method	Flow External Area
Infiltration Rate	0.0005689 m³/s/m²

In contrast to the default ASHRAE values, the Coefficient of Performance (COP) of the heating and cooling systems are modified. The standard ASHRAE zone template assumes a heating COP of 0.81, which represents an inefficient gas boiler (Vakkilainen, 2017)). In the assessment, a COP of 3.5 is adopted for both heating and cooling, which can be achieved currently by installing heat pumps (International Energy Agency, 2022)). Additionally, the heat recovery efficiency is adjusted from 0.7 and 0.5 for sensible and latent heat respectively to a uniform 0.8, aligning with already achievable values for this type of technology (Liu et al., 2024)).

While this approach may seem to contradict the renovation focus mentioned earlier, it is deemed a more realistic scenario, anticipating advancements in technology and overall improvement of the system's efficiency over 50 years.

Scenario B

Figure 17 depicts the energy model considered in Scenario B, representing the geometry of the interior surfaces of the space. The windows are placed on the South-facing wall, including the surfaces representing the exterior wall 300 mm thickness. Windows are modelled as single surfaces on the interior wall. Lastly, the room is placed on the ground, defining the boundary conditions of the floor.

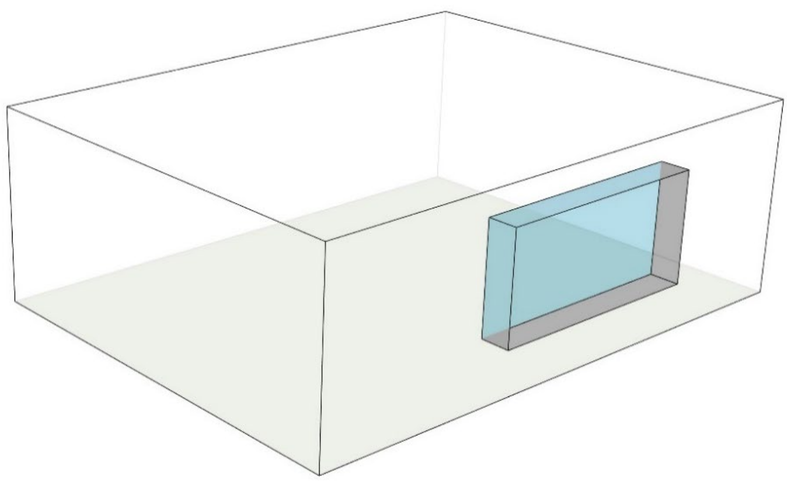

Figure 17: Energy model used for the simulations in ClimateStudio in Scenario B.

The zone settings for scenario B can be found in **Error! Reference source not found.**. These settings are based on the ClimateStudio zone template named 90.1-2019 MediumOffice – OpenOffice CZ 5 based on the ASHRAE standard and adapted to most appropriate programme type and Lund's climate zone. A detailed breakdown of the schedules considered is in Table 34 andTable 35 in **Annex B**. Simulation parameters. Finally, like in Scenario A, the COP and heat recovery systems considered are 3,5 and 80% respectively, in order to represent and more plausible future scenario.

Table 26: *Zone settings considered in Scenario B, based on ASHRAE 90.1* (ASHRAE, 2019))

Settings	**Value**
People density	0.057 p/m²
Metabolic rate	1.2 met
Occupancy Schedule	OfficeMedium BLDG_OCC_SCH
Equipment Load	10.33 W/m²
Equipment Availability Schedule	OfficeMedium BLDG_EQUIP_SCH_2013
Lighting Power Density	6.57 W/m²
Illuminance Targe	375 lux
Lights Availability Schedule	OfficeMedium BLDG_LIGHT_SCH_2013
Dimming Type	Off
Heating Setpoint	Based on OfficeMedium HTGSETP_SCH_NO_OPTIMUM
Max Heat Supply Air Temperature	30 °C
Heating COP	3.50
Max Heating Capacity	100 W/m²
Max Heat Flow	100 m³/s/m²
Cooling Setpoint	Based on OfficeSmall CLGSETP_SCH_NO_OPTIMUM
Min Cool Supply Air Temperature	18 °C
Cooling COP	3.50
Cooling & Heating Limit Type	No Limit
Max Cooling Capacity	100 W/m²
Max Cool Flow	100 m³/s/m²
Min Fresh Air Per Person	2.36 l/s/p
Min Fresh Air Per Area	0.30 l/s/m²
Heat Recovery Type	Enthalpy
Heat Recovery Efficiency Sensible	0.80
Heat Recovery Efficiency Latent	0.80
Infiltration Calculation Method	Flow External Area
Infiltration Rate	0.0002266 m³/s/m²

4.3 Life-Cycle Impact Assessment (LCIA)

As outlined in **3.3.1. Environmental impact categories**, the impacts in this study are reported using the GWP100 indicator based on in the latest IPCC Assessment Report, in kgCO_2-eq.

4.4 Life-Cycle Interpretation

4.4.1. Analysis of the results

Scenario A

Daylight provision results

The daylight simulations performed provide the results detailed in Table 27, based on the dimensions of the systems outlined in section **0. Bill of materials**. As established in the FU, both systems reach a DFm of at least 1%, being precisely 1.06% for the baseline and 1.01% in the novel system. Figure 18 illustrates the DF outcomes distributed in the room space. Table 27 contains the results for other metrics, which are optional to report but help providing an overall understanding of the daylight performance in the space.

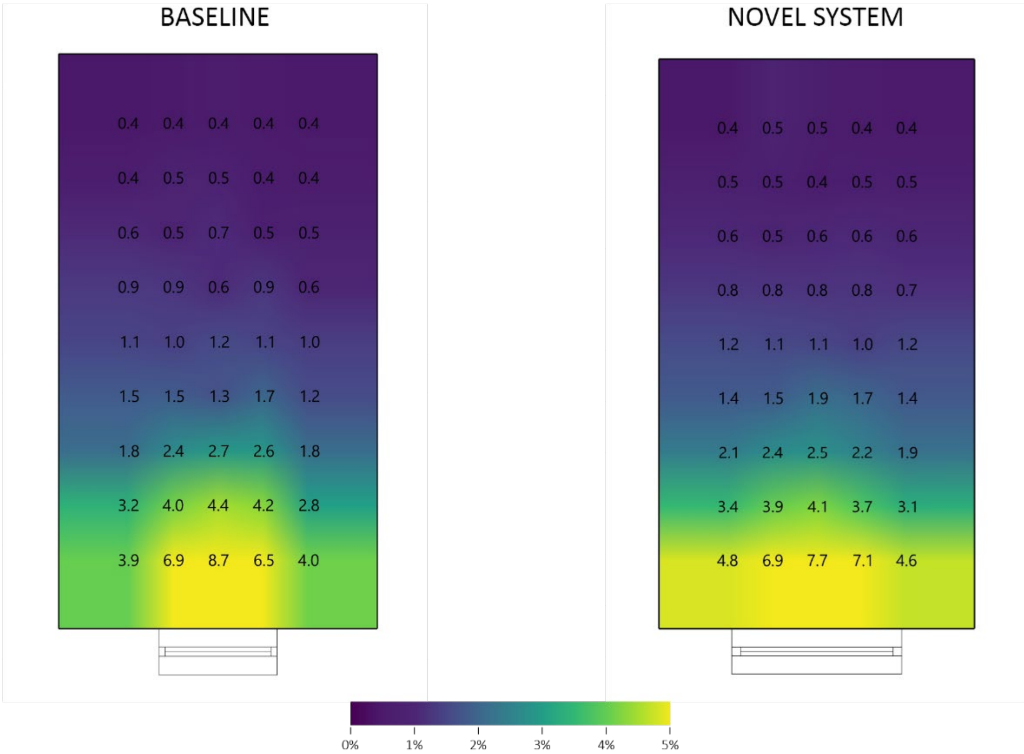

Figure 18: DF results for the baseline and the novel system in Scenario A.

Table 27: Daylight results for the baseline and the novel system in Scenario A for several additional metrics.

Metrics	Baseline System	Novel System
ADF	1.85%	1.88%
Failing UDI (<100lx)	19.47%	43.10%
Supplemental UDI (100 to 300 lx)	21.42%	24.06%
Autonomous UDI (300 to 3000 lx)	54.20%	32.32%
Excessive UDI (> 3000 lx)	4.91%	0.52%
ASE	20.00%	28.89%
DA	59.11%	32.84%
sDA	68.89%	22.22%

Indoor comfort results

The indoor comfort was assessed in the room considering both systems, and Figure 19 displays the hourly temperature results in the room. The baseline system results in 36 hours where the operative temperature exceeds 26°C, while the novel system experiences only 27 hours under the same conditions. Both cases fall below 1% of the hours between April and September, significantly lower than the 10% threshold mentioned in section **0. Indoor comfort results**.

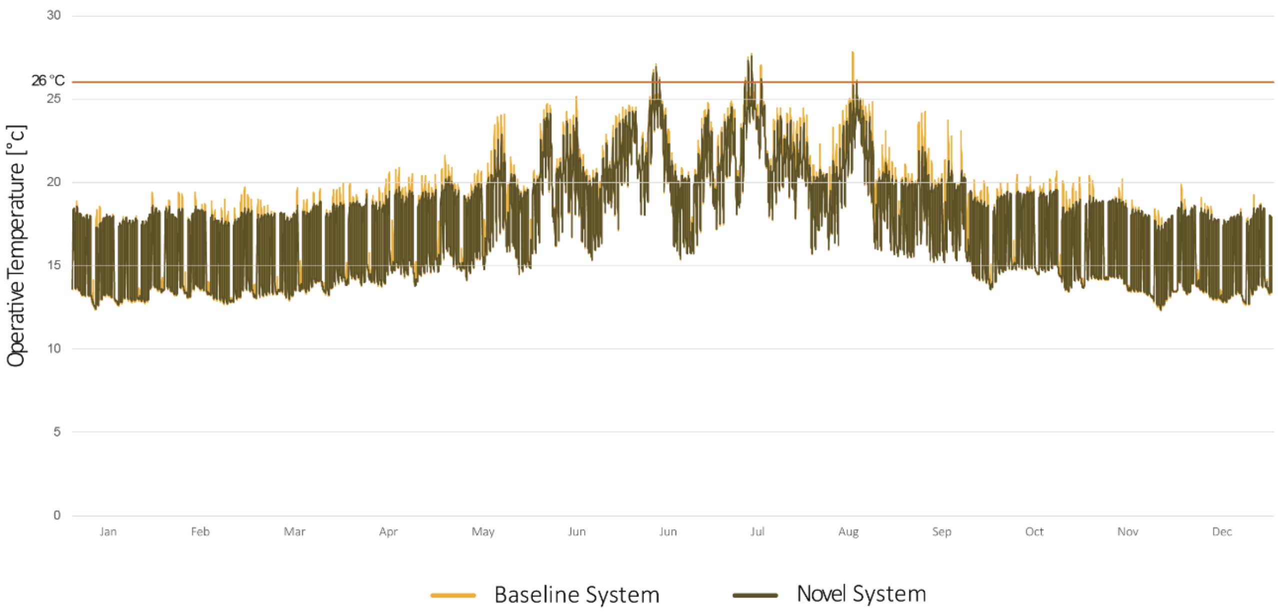

Figure 19: Operative temperature inside the space for both systems in Scenario A.

Energy performance results

The energy simulations performed in both for both systems yield an EUI of 196.4 kWh/m²/year for the baseline and 197.3 kWh/m²/year for the novel solution. This is caused by the geographical context selected as the higher g-value of the baseline, in a Swedish context, results in a reduction of the heating needs that compensate the increase due to poorer U-value. If these systems were assessed in cooling dominated countries, these results would probably be very different. Considering a period of 50 years and given that the area of the space is 13.8 m², the total energy consumption is 135 516 kWh and 136 137 kWh, respectively, resulting in an energy difference of 621 kWh.

GWP results

The GWP results, derived from the inputs detailed in the previous sections, can be found in Table 28. This table contains the absolute GWP results over a 50-year period, categorised by the LCA module. Figure 20 shows the results of the novel system normalised by the FU.

Upon initial observation, the emissions resulting from the energy usage in buildings are the most significant component of this system, accounting for up to 98% and 90% of the total global warming potential in the baseline and the new system, respectively.

Figure 20Table 28: GWP results over 50 years for the baseline and the novel system in Scenario A.

Section	Category	Baseline GWP (kgCO$_2$-eq)	Novel system GWP (kgCO$_2$-eq)
A1-A3	Construction Materials	1.02E+02	3.55E+02
B4	Replacement	1.02E+02	7.11E+02
B6	Energy consumption	1.08E+04	1.08E+04
Total		**1.10E+04**	**1.19E+04**

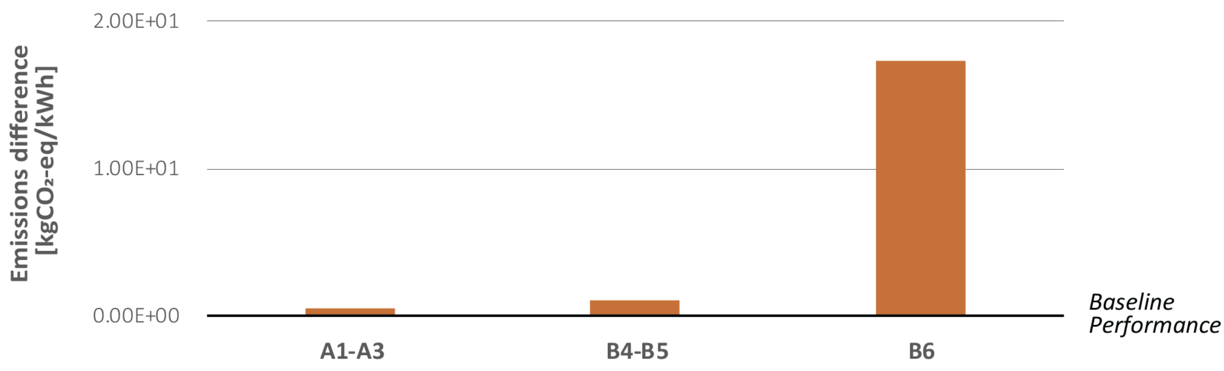

Figure 20: GWP results referred by the FU in scenario A.

Scenario B

Daylight provision results

Figure 21 illustrates the distribution of DF across the studied space, based on the dimensions outlined in section **0. Bill of materials**. Of course, both spaces comply with a minimum DFm of 1%, in this case reporting exactly 1%. Other alternative daylight metrics are reported in

Table 30.

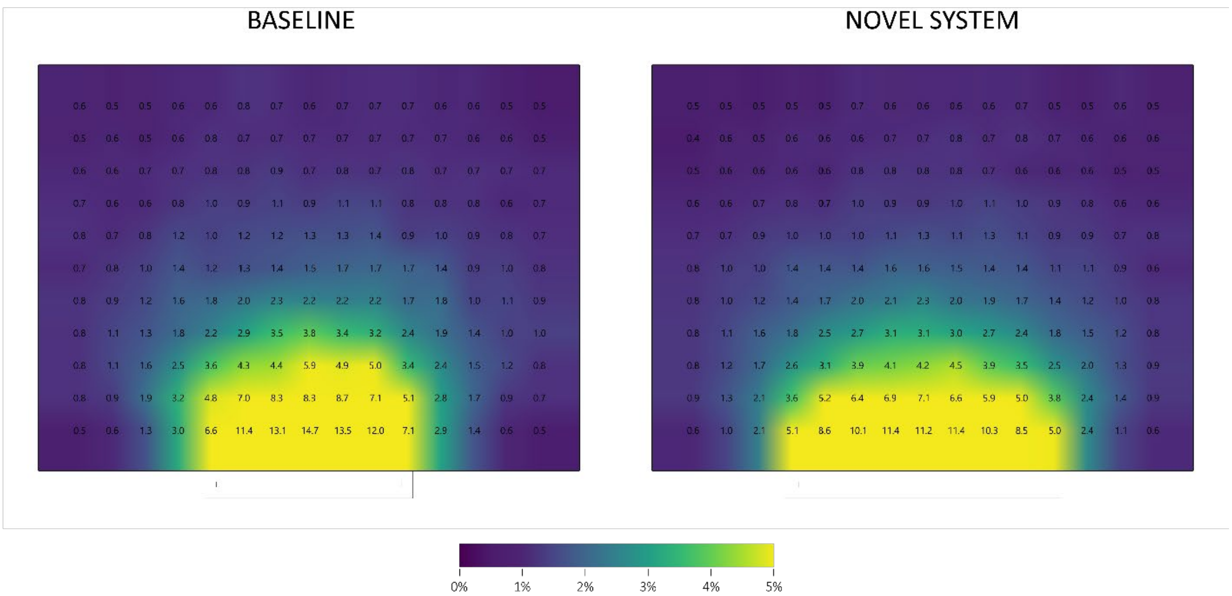

Figure 21: DF results for the baseline and the novel system in Scenario B.

Table 29: Daylight results for the baseline and the novel system in Scenario B for several additional metrics.

Metrics	Conventional	Novel solution
ADF	1.97%	1.90%
Failing UDI (<100lx)	18.73%	48.91%
Supplemental UDI (100 to 300 lx)	17.96%	19.78%
Autonomous UDI (300 to 3000 lx)	56.78%	30.55%
Excessive UDI (> 3000 lx)	6.53%	0.76%
ASE	22.42%	27.27%
DA	63.31%	31.31%
sDA	81.21%	14.55%

Indoor comfort results

Figure 22 displays the operative temperature inside the space at an hourly resolution, taking into account both systems. It is possible to observe that the temperature in the room is basically the same overall and the total results in room based on the threshold mentioned in section **0. Indoor comfort results** are the same, with only 3 hours above 26°C in both systems.

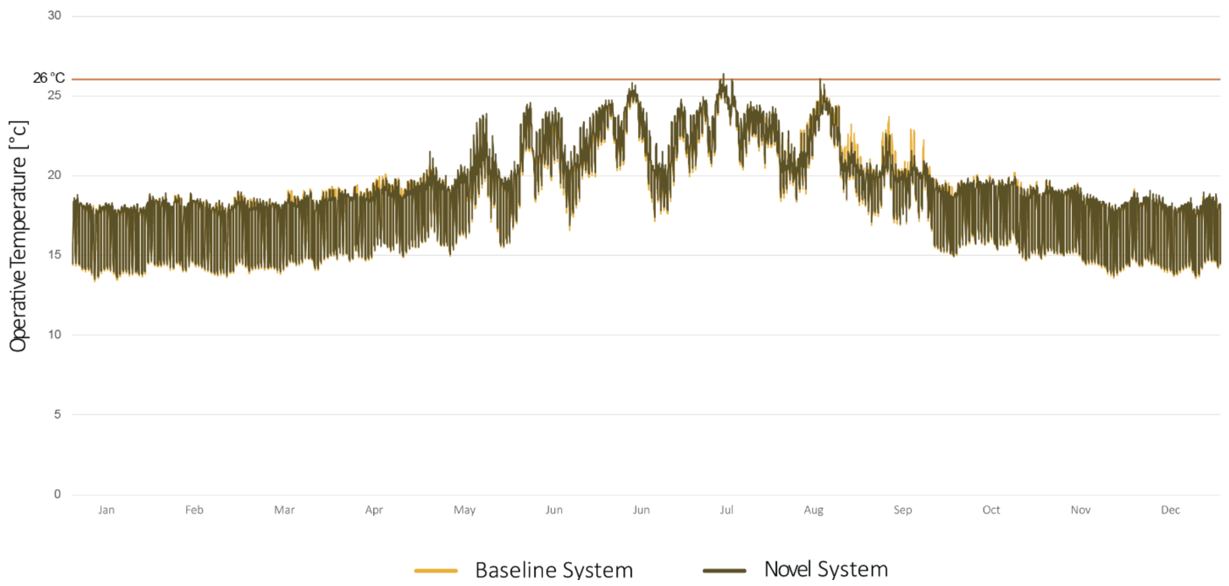

Figure 22: Operative temperature inside the space for both systems in Scenario B.

Energy performance results

In this scenario, the EUI of the baseline resulted in 120.1 kWh/m²/year, while the novel system yields a result of 120.9 kWh/m²/year. Considering the size of the space and the 50-year period, the total energy consumption of the building is 288 240 kWh and 290 160 kWh, resulting in an energy consumption difference of 1 920 kWh.

GWP results

Table 30 contains the GWP results in Scenario B for both systems, grouped by LCA module, and following the template proposed in section **0. GWP results.** Additionally, Figure 23 shows the difference GWP referred by the FU.

As well as in Scenario A, the novel system presents a worse performance than the baseline, resulting in positive results when the GWP results are normalized by the FU. It is as well important to note that, even though the results for the novel system are overall higher than in the baseline for the embodied and the operational part, the energy consumption is the driving factor of the results for both systems.

Lastly, to put into perspective the difference in performance between both systems, for the novel system to have the same total GWP as the baseline, the EUI would have to be 107.7 kWh/m²/year instead of the current 120.9 kWh/m²/year.

Table 30: GWP results over 50 years for the baseline and the novel system in Scenario B.

Section	Category	Baseline GWP ($kgCO_2$-eq)	Novel system GWP ($kgCO_2$-eq)
A1-A3	Construction Materials	2.26E+02	9.34E+02
B4	Replacement	2.27E+02	1.87E+03
B6	Energy consumption	2.29E+04	2.30E+04
Total		**2.33E+04**	**2.58E+04**

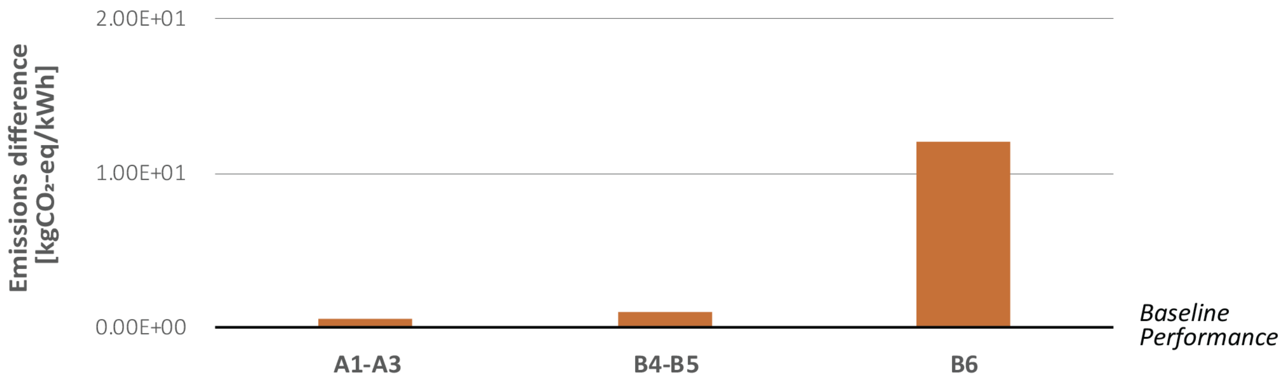

Figure 23: GWP results referred by the FU in scenario B.

4.4.2 Aggregation method

As explained in the section **0.**

Table 15: Suggested table template for the presentation of the GWP results.

Section	Category	Baseline GWP ($kgCO_2$-eq)	Novel system GWP ($kgCO_2$-eq)
A1	Raw material supply		
A2	Transport		
A3	Manufacturing		
A4	Transport		
A5	Construction Process		
B1	Use phase		
B2	Maintenance		
B3	Repair		
B4	Replacement		
B5	Refurbishment		
B6	Energy consumption		
B7	Water use		
C1	Deconstruction		
C2	Transport		
C3	Waster Processing		
C4	Disposal		
D	Reuse/Recovery/Recycle		
Total			

Additionally, this methodology highly recommends creating a graph to display the difference in performance between the baseline and the assessed system. Figure 8 shows a suggested graph in which the baseline performance represents the benchmark value, while the variation on the performance is displayed by the bars. They represent an improvement in the performance compared to the baseline when the results are negative, or a worsening, when the values are positive.

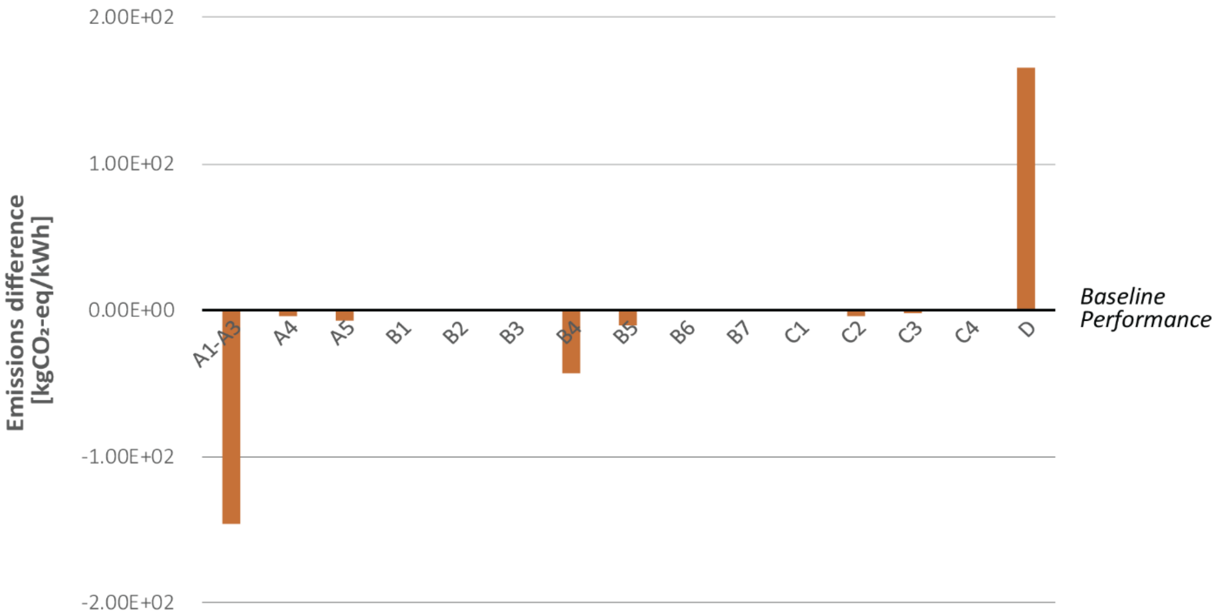

Figure 8: Suggested graph template for the presentation of the GWP results.

Aggregation method of the harmonised methodology, the methodology focuses on a single environmental impact, the GWP, so there is no need for the application of weighting or normalising factors.

4.4.3 Uncertainty and sensitivity analysis

As detailed in section **3.4.3. Uncertainty and sensitivity analysis**, the incorporation of these analysis is recommended to increase the robustness and accuracy of the results, enhancing the understanding of the main contributing factors.

Several factors could benefit from this approach. First, by varying the maintenance scenario, the influence of varying the products' lifespan could be studied. Second, examining the impacts of the system across different contexts, including various locations in different climate conditions. Additionally, the study could extend beyond the renovation context, considering highly efficient HVAC systems and appropriate building envelope. Furthermore, it would be interesting to observe the performance of the system in different orientations. Finally, considering different energy source scenarios would allow for further testing the influence of the energy context in the life cycle of the system.

5 Discussion

The discussion is structured into three main sections. The two initial sections provide a comprehensive analysis of the results obtained from the application of the methodology to the case studies and the finding obtained from the development of the methodology itself. The final section explores potential paths to research derived from the insights and findings in the first two sections.

5.1 Methodology application

5.1.1 Daylight performance

The study revealed a size difference ranging between 7% and 10% between the baseline and the novel system, due to the lower Tvis of the latter. These results are consistent with the initial expectations based exclusively on the systems' characteristics. Additionally, it is important to highlight that the clearest tint is considered for the EC glazing; a darker tint would increase these differences even further.

Furthermore, the results obtained in different daylight performance metrics beyond DFm reveal significant differences depending on the metric considered. For instance, the novel system resulted in lower UDI and sDA results, despite both having the same DFm. This discrepancy raises important considerations regarding the suitability of using DFm as the criterion for daylight quality in the FU, a topic further discussed in section **5.2.2. Daylight quality threshold**.

5.1.2 Indoor thermal comfort

The selected HVAC settings, coupled with the temperatures in Lund, result in minimal overheating hours, significantly below the reference threshold set in the methodology. In these settings, the consideration for indoor thermal comfort could be almost omitted. However, the experience suggests that this aspect may have a more pronounced effect in different regions, especially those with higher cooling demands.

5.1.3 Energy performance

The geographical context selected significantly influenced the energy results, highlighting the importance of the climate differences. The application of the framework resulted in the novel system having higher EUI than the baseline, primarily due to the higher g-value the baseline presents. In a Swedish context, this variation has a high impact in reducing the heating needs by increasing the higher solar gains. If this assessment was performed in a cooling-dominated country, this difference would probably yield energy savings instead.

In addition, the application of the methodology considered most of the HVAC settings based on the standard ASHRAE 90.1-2019. While this is one of the approaches recommended in the methodology, its applicability beyond American contexts is questionable. The decision to follow this standard aimed to streamline the process, utilizing standardized values integrated in the simulation software, instead of researching for other sources. However, HVAC settings significantly influence the overall energy results and, given the methodology's dependency on the energy results, exploring more geographically relevant values could have provided valuable insights.

5.1.4 GWP results

The GWP results obtained reflect the influence of the context considered, defined not only by the geographical factors, but also the building characteristics and the duration of the study period. For instance, in typical scenarios of renovations, particularly considering a 50-year analysis period, the GWP associated with operational energy (B6) accounts for approximately 90%-98% of the total environmental impact. In such contexts, the importance lies on reducing the operational energy. However, in a context characterized by low energy consumption, the importance of the operational GWP is reduced and it would increase the importance of the choice of materials, maintenance scenario, or replacement frequency.

However, not only the energy consumption and the timeframe result in GWP differences, but the energy source also plays a pivotal role as well. In scenarios representing countries heavily reliant in fossil fuels, the B6 impacts would be the highest contributor. Even in this assessment, despite the low GHG emissions of the European context, the results for B6 remained notably high.

Furthermore, the impact of operational energy tends to overshadow the difference in the embodied impact of the daylight systems. Notably, the EC glazing system presented a much higher impact from the materials, between two to five times higher, depending on the LCA module, consequence of the higher amount of material needed and the assembly of a more complex system, coupled with its lower lifespan. In order to balance this increase in embodied carbon, the novel system would need to provide high energy savings, which, in this case, fails to do.

5.2 Harmonised methodology development

5.2.1 Study period

Selecting a fixed 50-year study period allows for a holistic understanding of the daylight system's impacts within a space. This duration allows for an evaluation that includes indoor daylight quality, indoor comfort as well as energy performance and environmental impacts. The choice of 50 years, based on Level(s) Framework, seems appropriate to fully encapsulate the total impact of the system. Shorter or longer periods might distort the analysis, either by minimising the impact of materials' lifespan or compromising accuracy on the estimations considered. However, the choice of such a long period might shadow the impact of the materials in certain contexts, due to the overrepresentation of the operational emissions, highlighting the need for evaluation approaches which are context sensitive.

5.2.2 Daylight quality threshold

The FU daylight quality threshold is currently based on the DFm, and this might not fully encapsulate the daylight performance of the space. This metric was selected to include a broader range of systems within the scope of the assessment, as setting an overly strict daylight quality threshold would result in many systems not being able to reach the minimum performance and thus ineligible for assessment. At the same time, this approach aims to ensure a baseline level of daylight quality, based on a metric that remains widely utilized.

However, this approach might fall short in capturing the nuanced performance of different lighting systems. Have climate-based metrics, such as DA or UDI, been selected instead of DFm, results could have been more contextually relevant, and they might have offered a more accurate reflection of a system's performance in different climates and spatial contexts.

Additionally, another alternative could be aligning the minimum daylight performance thresholds with local standards or regulations. This approach would allow for performance levels tailored to specific climatic conditions. However, this method would face the challenge of the difference in demands within local regulations, which can range from very restrictive to non-existent.

5.2.3 Whole life carbon assessment

Implementing a comprehensive life carbon assessment has been crucial in gaining a thorough understanding of the system's impact. While incorporating every LCA module may not be possible, the application of the methodology to a case study have demonstrated that concentrating on just one stage is restrictive and could lead to missing important information.

The decision on which modules to include and exclude is context sensitive, as the relevance can vary. It is common that comparative assessments focus exclusively on the embodied carbon of a product. However, a holistic approach needs to consider factors beyond initial production, such as replacement frequency and end-of-life scenarios, even when operational energy is intentionally excluded from the study. This highlights of performing LCA assessments that cover various lifecycle stages to ensure a more comprehensive evaluation.

5.3 Further development

Several aspects have emerged for future research and potential development. Firstly, a critical area to explore involves the definition of the FU. Previously, it was analysed the limitations of including the DFm as the threshold for daylight quality in the space, pointing towards climate-based metrics as potential alternatives. This exploration is needed to understand the effect of setting different thresholds, and probably stricter, and how the performance would differ from the current definition of the FU.

Additionally, integrating daylighting and electric lighting seems a reasonable progression in refining the methodology. This integration would require a revision in the FU in order to combine metrics that accurately represent daylight and electric lighting, or even setting two different thresholds for each type of light. Moving towards a scenario that factors in sensors or dimming capabilities would provide a more detailed view of the energy consumption and would offer a more realistic picture of the situation in the space.

Furthermore, the importance of exploring different scenarios cannot be overstated. By exploring different energy scenarios and incorporating future climate data into sensitivity analyses, a more comprehensive understanding of potential future impacts can be gained. This is especially important considering the long study period this assessment establishes, as climate change could significantly impact future energy demands and daylighting strategies.

In addition, there is a compelling need to validate the adaptability and flexibility of the methodology to different conditions. By testing different climatic scenarios and building performance, for example by modifying parameters like U-values, internal loads, HVAC settings or even the geographical context, the adaptability of the methodology to different conditions could be proved. As of now, the methodology has only been tested in a single scenario, but understanding how these adjustments influence factors such as energy consumption and thermal comfort in different settings is crucial.

Together, these are some of the areas that could be further explored in this methodology and would allow achieving a more robust, and adaptable framework.

6 Conclusion

This work focused on developing a harmonised methodology for the evaluation of daylighting systems. Several takeaways can be extracted after the development of the methodology and the later application to two study cases:

- Minimum daylight performance: Including a requirement of achieving a minimum daylight performance underscores the importance of considering space daylighting quality, separating this methodology from the traditional methodologies that focused solely on the environmental aspect, regardless of the quality of the space these systems were on. This aspect emphasises the holistic nature of the methodology.
- Clear baseline definition: The proposed methodology contains a clear definition of a baseline, enhancing the evaluation process by providing a concrete system to measure against. This clarity allows for setting a clear distinction between well-performing and poorly performing systems and simplifying the decision of which one is environmentally preferable. This is particularly suitable for comparative assessments including several novel systems.
- Contextual and holistic life cycle approach: Considering the system in a building context and including a cradle-to-grave LCA approach, as well as considering a fixed study period, allows to consider the whole life of the system. This ensures that the systems are selected based on their overall environmental footprint and not exclusively the manufacturing impacts, promoting more informed and overall sustainable decisions.

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Annex A. Materials characteristics

Table 31: Characteristics of the materials used in the simulations. Layers from inside to outside.

Component	Materials	Thickness (mm)	Density (kg/m³)	Thermal conductivity (W/m/K)	Specific Heat (J/kg/K)
Roof	Concrete	300	2 400	2.000	950
	Mineral Wool	25	105	0.040	1 800
Wall	Concrete	300	2 400	2.000	950
	Mineral Wool	20	105	0.040	1 800
Floor	Cement Screed	50	2 000	1.400	1 000
	Concrete	300	2 400	2.000	950
	Mineral Wool	25	105	0.040	1 800

Annex B. Simulation parameters

Table 32: Occupancy, lighting, and equipment schedule considered in Scenario A.

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

Table 33: Heating and cooling setpoints considered in Scenario A.

Hour	Heating Setpoint		Cooling Setpoint	
	Mon-Sat	Sun	Mon-Sat	Sun
1	15.6	15.6	29.4	29.4
2	15.6	15.6	29.4	29.4
3	15.6	15.6	29.4	29.4
4	15.6	15.6	29.4	29.4
5	15.6	15.6	29.4	29.4
6	15.6	15.6	29.4	29.4
7	21.1	15.6	23.9	29.4
8	21.1	15.6	23.9	29.4
9	21.1	15.6	23.9	29.4
10	21.1	15.6	23.9	29.4
11	21.1	15.6	23.9	29.4
12	21.1	15.6	23.9	29.4
13	21.1	15.6	23.9	29.4
14	21.1	15.6	23.9	29.4
15	21.1	15.6	23.9	29.4
16	21.1	15.6	23.9	29.4
17	21.1	15.6	23.9	29.4
18	21.1	15.6	23.9	29.4
19	21.1	15.6	23.9	29.4
20	15.6	15.6	29.4	29.4
21	15.6	15.6	29.4	29.4
22	15.6	15.6	29.4	29.4
23	15.6	15.6	29.4	29.4
24	15.6	15.6	29.4	29.4

Table 34: Occupancy, lighting, and equipment schedule considered in Scenario B.

Hour	Occupancy Schedule		Lighting Schedule		Equipment Schedule	
	Mon-Sat	Sun	Mon-Sat	Sun	Mon-Sat	Sun
1	0.00	0.00	0.05	0.05	0.30	0.20
2	0.00	0.00	0.05	0.05	0.30	0.20
3	0.00	0.00	0.05	0.05	0.30	0.20
4	0.00	0.00	0.05	0.05	0.30	0.20
5	0.00	0.00	0.05	0.05	0.30	0.20
6	0.00	0.00	0.10	0.05	0.30	0.20
7	0.10	0.10	0.10	0.10	0.40	0.40
8	0.20	0.10	0.30	0.10	0.40	0.40
9	0.90	0.30	0.80	0.30	0.90	0.50
10	0.90	0.30	0.80	0.30	0.90	0.50
11	0.90	0.30	0.80	0.30	0.90	0.50
12	0.90	0.30	0.80	0.30	0.90	0.50
13	0.50	0.10	0.80	0.10	0.75	0.35
14	0.90	0.10	0.80	0.10	0.90	0.35
15	0.90	0.10	0.80	0.10	0.90	0.35
16	0.90	0.10	0.80	0.10	0.90	0.35
17	0.90	0.10	0.80	0.10	0.90	0.35
18	0.30	0.05	0.40	0.05	0.50	0.30
19	0.10	0.05	0.30	0.05	0.40	0.30
20	0.10	0.00	0.30	0.05	0.40	0.20
21	0.10	0.00	0.20	0.05	0.40	0.20
22	0.10	0.00	0.20	0.05	0.40	0.20
23	0.05	0.00	0.10	0.05	0.40	0.20
24	0.05	0.00	0.05	0.05	0.40	0.20

Table 35: Heating and cooling setpoints considered in Scenario B.

Hour	Heating Setpoint		Cooling Setpoint	
	Mon-Sat	Sun	Mon-Sat	Sun
1	15.6	15.6	26.7	26.7
2	15.6	15.6	26.7	26.7
3	15.6	15.6	26.7	26.7
4	15.6	15.6	26.7	26.7
5	15.6	15.6	26.7	26.7
6	17.8	17.8	25.6	25.6
7	20.0	20.0	25.0	25.0
8	21.0	21.0	24.0	24.0
9	21.0	21.0	24.0	24.0
10	21.0	21.0	24.0	24.0
11	21.0	21.0	24.0	24.0
12	21.0	21.0	24.0	24.0
13	21.0	21.0	24.0	24.0
14	21.0	21.0	24.0	24.0
15	21.0	21.0	24.0	24.0
16	21.0	21.0	24.0	24.0
17	21.0	21.0	24.0	24.0
18	21.0	15.6	24.0	26.7
19	21.0	15.6	24.0	26.7
20	21.0	15.6	24.0	26.7
21	21.0	15.6	24.0	26.7
22	21.0	15.6	24.0	26.7
23	15.6	15.6	26.7	26.7
24	15.6	15.6	26.7	26.7

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