



Beyond Carbon: Integrating Biodiversity Impact Assessment in Building Design Practice

A tool to evaluate off-site biodiversity impacts of the built environment

Master's thesis in Industrial Ecology

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MASTER'S THESIS ACEX30

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Cover:

Visualization of case study results and tool outputs. Further details are provided in Chapter 4.

Department of Architecture and Civil Engineering
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ABSTRACT

The increasing focus on decarbonisation in the building sector has intensified the use of bio-based construction materials. However, climate-driven strategies do not fully capture broader environmental consequences, particularly regarding biodiversity loss. This thesis investigates the relationship between biodiversity impacts and global warming potential, examining how design decisions and material sourcing influence the environmental performance of buildings.

A comparative case study approach is applied, assessing conventional concrete structures alongside several timber-based alternatives. The results show that reductions in carbon emissions may simultaneously increase off-site biodiversity impacts, revealing potential burden-shifting between environmental categories. At the same time, considerable variation is identified within timber-based systems, demonstrating that bio-based construction is not inherently associated with high biodiversity impacts. Cross-laminated timber (CLT) generally has higher impacts, while timber frame systems perform favourably across both carbon and biodiversity indicators. The analysis further highlights geographical sourcing as a critical factor, with Nordic and Central European timber showing substantially lower impacts than global average datasets, highlighting the importance of more detailed material considerations and structural design decisions.

To explore how the biodiversity assessment can support practice, a computational tool is developed to integrate biodiversity footprint (BF) evaluations into architectural workflows. Building on life cycle assessment methods, the framework enables simplified comparison of design alternatives and identification of environmental hotspots at both building and component level, addressing the need for more accessible tools in the design process. Although constrained by methodological uncertainty and limited data availability, the study demonstrates how biodiversity considerations can support iterative evaluations and contribute to broader environmental decision-making in the building sector.

Overall, the thesis shows that biodiversity impacts cannot be understood through carbon metrics alone. The study highlights the importance of integrating biodiversity as a complementary dimension in order to support more holistic sustainability strategies within the built environment.

Key words: Biodiversity impacts, Life cycle assessment, Computational tools, Sustainable building design

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Preface

This study explores the integration of off-site biodiversity assessment into early-stage life cycle assessment (LCA) through literature reviews, interviews, and workshops, resulting in the development of a digital design tool further explored through a series of case studies. The report is the outcome of a 30 ECTS Master's thesis within the Master's Programme in Industrial Ecology at Chalmers University of Technology, carried out between January and June 2026.

The work has been conducted at the Department of Architecture and Civil Engineering, Division of Building Technology, with external supervision from CF Møller Architects in Copenhagen. The project has been carried out under the supervision of Haitham Ghaida, with Associate Professor Alexander Hollberg serving as examiner. I would like to thank them for their support, guidance, and feedback throughout the project, as well as for sharing their expertise in the field of LCA and digital tool development.

A special thanks to the sustainability team at CF Møller Architects, in particular Charlie Bo Bøjsen Møller and Rob Marsh, whose engagement and generosity have been invaluable throughout the project. Their continuous willingness to share knowledge, resources, and ideas, has significantly contributed to the direction and quality of this work. They have provided endless expertise and professional networks within the intersection of sustainability and architectural design, along with continuous inspiration and encouragement throughout the research process. Finally, I would also like to express my gratitude to my opponent, Frida Björklund, for valuable thoughts and discussions.

Gothenburg, June 2026

Albina Lampa

Abbreviations

BBV	The project “Biodiversity impact from the building industry value chain”
BEF	Biodiversity and Ecosystem Functioning
BF	Biodiversity Footprint
BIM	Building Information Modelling
CF	Characterization Factors
CO ₂ e	Carbon dioxide equivalents
DGNB	German Sustainable Building Council
EPD	Environmental Product Declaration
GFA	Gross Floor Area
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
TDN	Lost Danish nature equivalents

Life cycle phases for buildings

A1-A3	Production
A4-A5	Construction and installation
B1-B7	Use
C1-C4	End-of-life
D	Benefits and loads

1. Introduction

In this chapter, the background, aim and objectives, research questions, delimitations as well as the audience of the thesis are introduced. Lastly, an outline of the thesis structure is presented.

1.1 Background

Loss of biodiversity is one of the largest global crises facing society today. According to the planetary boundaries framework (Figure 1) proposed by Rockström et al (2009), biosphere integrity has already surpassed a safe operating limit, stating that human-driven land-use change has accelerated species extinction rates to 100–1,000 times above natural levels. Currently, around 25% of species are further threatened with extinction and the availability of natural ecosystems have drastically declined since pre-industrial times (IPBES, 2019). In response to these trends, many countries have committed to taking urgent action to halt biodiversity loss by 2030, as part of the Kunming-Montreal Global Biodiversity Framework adopted at COP15 (UNEP, 2022). Achieving these ambitions requires improved understanding of where biodiversity impacts occur and what drives them.

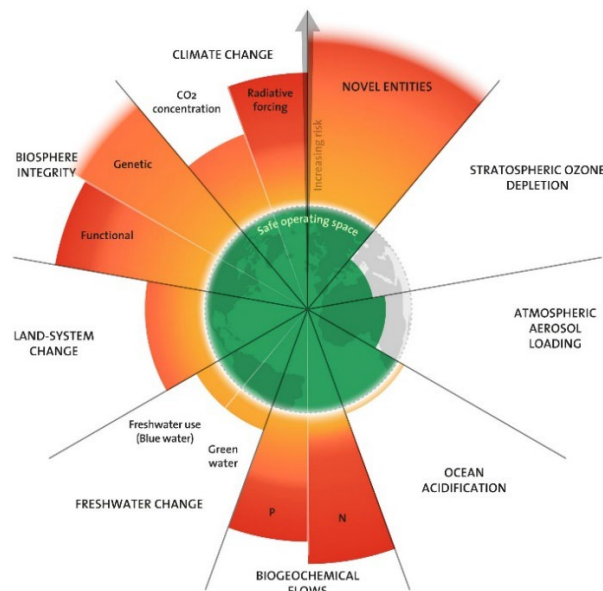


Figure 1. The planetary boundaries (Rockström et al., 2009)

The building sector plays an important role in this context due to its extensive material consumption and resource use. The sector is responsible for approximately 34% of global greenhouse gas emissions (UNEP, 2025), and environmental efforts have therefore largely focused on reducing climate impacts through decarbonization strategies. While this represents an important step in the green transition. The growing focus on decarbonization can create a tunnel-vision, where efforts to reduce greenhouse gas emissions may overlook other environmental impacts (Léonard *et al.*, 2026).

Recent research shows that buildings can contribute significantly to biodiversity loss through the upstream value chains (Winter *et al.*, 2017; Francart *et al.*, 2024; Sigvert *et al.*, 2025). The

Danish study *Biodiversitetspåvirkning fra 50 byggerier* found that approximately 95% of total biodiversity impacts originated from off-site processes such as raw material extraction, material production, and energy supply, while materials alone accounted for 78% of total impacts (Upstream Partners *et al.*, 2025). Despite this, biodiversity impacts in the building sector are often primarily addressed on the project site, while off-site effects related to material production, land-use and energy supply remain poorly understood. As a result of this knowledge gap, current decarbonisation strategies and policies risk influencing biodiversity in ways that are not yet fully recognised or accounted for (Francart *et al.*, 2024).

Developing methods that allow biodiversity impacts to be assessed alongside climate impacts has therefore gained increasing interest. Introducing biodiversity as an additional indicator within building Life Cycle Assessment (LCA) frameworks represents a significant opportunity toward more holistic environmental evaluation. Though, data availability and methodological uncertainties currently hinder the implementation of biodiversity assessment in building LCA, highlighting the need for accessible tools that can support professionals in evaluating ecological damage of building projects and design decisions.

Recent advancements have been made in tools that translate LCA results into preliminary biodiversity impact estimations, yet there remains a lack of practical tools that enable professionals to identify biodiversity impact hotspots throughout the building design process, in order to integrate this information into design decisions (Francart *et al.*, 2024).

This thesis addresses this gap by investigating how biodiversity impacts can be integrated into design workflows through a computational design tool framework. The study further explores how biodiversity impacts vary across structural systems and building components, and how they relate to Global Warming Potential (GWP), with the aim of supporting more informed environmental decision-making in the building industry.

1.2 Aim & Objectives

The aim of this thesis is to investigate how off-site biodiversity impact assessment can be integrated into architectural workflows through the development of a digital tool, and to explore the value of incorporating biodiversity considerations into design decision-making. The tool builds on existing LCA methodologies for biodiversity impact assessment and provides a simplified means of estimating impacts to support decision-making and hotspot analysis. The tool seeks to support comparison of GWP and BF across building components, constructions, and materials, while maintaining a balance between usability and analytical depth.

The main objectives of the thesis are to:

- Review existing methodologies for assessing biodiversity impacts within LCA framework
- Investigate the architectural design process to identify requirements for integrating biodiversity impact assessment
- Develop and implement a framework for a parametric tool that operationalizes the estimation of BF and GWP based on building geometry.

- Analyse and compare how BF and GWP performance of buildings interact
- Explore how the tool can support the design process and evaluate its limitations and uncertainties

1.3 Research Questions

Below, the research questions are presented.

- *How are biodiversity impacts associated with building projects **measured and represented within Life Cycle Assessment (LCA)**?*
- *How are sustainability considerations currently integrated into architectural design processes, and what **opportunities and challenges arise from incorporating biodiversity impacts** as an additional assessment dimension?*
- *How can a **digital tool framework** be used to connect off-site biodiversity impact assessment with building design models?*
- *How do **BF results vary across building types and in relation to GWP**, and how can the assessment be used to **inform design decisions**?*

1.4 Delimitations

This study focuses on the development and application of a simplified biodiversity impact assessment approach for building design. Several delimitations have been made to ensure feasibility and alignment with the project scope:

- The assessment is limited to **off-site biodiversity impacts**, primarily associated with material production, replacements and end-of-life stages. On-site biodiversity impacts, and the remaining stages of the use phase are excluded in the tool.
- Biodiversity impacts are assessed exclusively using the LCIA method Impact World+ v2.0.1. As a result, the outputs cannot be directly verified or compared with results from other assessment methods.
- The assessment relies on **generic and aggregated data** rather than product-specific data for biodiversity impacts, meaning results should **not be interpreted as exact measurements but potential impacts**.
- The developed tool is designed for **early-stage design support**, and therefore applies simplified assumptions regarding building geometry, material compositions, and life cycle parameters.

1.5 Audience

The primary audience for this thesis includes architects, engineers, and LCA practitioners engaged in sustainable building design and environmental assessment. The work is particularly relevant for professionals involved in decisions on material use and structural systems. The

results may also be of interest to developers, municipalities, certification bodies, and organisations working with sustainable procurement and environmental regulation. By linking biodiversity assessment to established building LCA workflows in the industry through computational design, the proposed tool aim to be compatible with current practice while contributing to the broader integration of biodiversity considerations in the built environment.

1.5 Thesis outline

The thesis report is structured into six main chapters: Introduction, Theory, Method, Results, Discussion, and Conclusion. The Introduction chapter presents the background on biodiversity loss and its connection to the built environment, followed by the scope of the thesis. The second chapter provides relevant theoretical foundations and an overview of previous research. The Method chapter describes the research approach, including the literature review, interviews, and workshops, as well as the framework for the development of the digital tool. Chapter four presents the resulting tool and its validation through case studies. This is followed by the Discussion chapter, which analyses the outcomes and reflects on limitations and opportunities for further development. Finally, the Conclusion summarises the key findings and insights of the thesis.

2. Theory

This chapter provides the theoretical foundation for the study and is structured in three main parts. The first part introduces the concept of biodiversity, establishes a working definition, and outlines key challenges associated with its assessment.

The second part describes biodiversity within the LCA framework, followed by a review on how to integrate biodiversity assessment based on LCA practice for building projects.

2.1 Defining biodiversity

In this section, the concept of biodiversity is examined, including its different dimensions and the main drivers of biodiversity loss. Lastly, the role of biodiversity in ecosystems is explored, providing a broader understanding of the ecological complexity and importance of functioning natural systems for human societies.

2.1.1 Levels of biodiversity

The Convention on Biological Diversity defines biological diversity as the variety of living organisms across all environments (terrestrial and aquatic), as well as the ecological networks they form. It is expressed through three ‘levels of biodiversity’, encompassing genetic variation within species, diversity of species and the diversity of ecosystems (United Nations (UN), 1992). Within biodiversity assessment research, ecosystem and species diversity remain the most represented indicators. Winter et al. (2017) found that 40% of biodiversity indicators focus on species diversity and 35% on ecosystem diversity, whereas only 4% address genetic diversity. This may cause misleading results as genetic diversity within species has been shown to significantly influence ecosystem functioning, in some cases contributing more to variation in biomass production than species diversity alone (Cardinale et al., 2012). Especially in times

of global change, the evolutionary adaptability and resilience of species is highly influenced by the genetic selection. This highlights the importance of considering all levels of biodiversity. Though, statistics show that genetic diversity may be the least urgent level of biodiversity loss. The WWF Living Planet Report (2024) estimates a 73% decline in global wildlife populations since 1970. Natural ecosystems also show a decrease by 47% (IPBES, 2019), where a lower estimation of 6% loss in genetic diversity is seen since the beginning of the industrial revolution (Leigh et al., 2019).

2.1.2 Drivers of biodiversity loss

According to the UN IPBES Global Assessment on Biodiversity and Ecosystem Services (2019), biodiversity loss has five direct drivers; land-/ sea use change, direct exploitation, climate change, pollution and invasive species (see Figure 2). Their relative contributions vary across terrestrial, freshwater, and marine environments. The report further states that human-induced land-use change primarily from forestry, agriculture, and urbanization, is identified as the leading driver across all three ecosystem types. This can to a large extent be explained by the growing population, which since 1992 has led to a doubling of urban areas, and over 1/3 of the world's land surface being devoted to crop or livestock production (IPBES, 2019). Further explained in the report, direct exploitation of natural resources has followed a similar trajectory, with the consumption of resources such as plants, animals, and construction materials increasing by 15% since 1980.

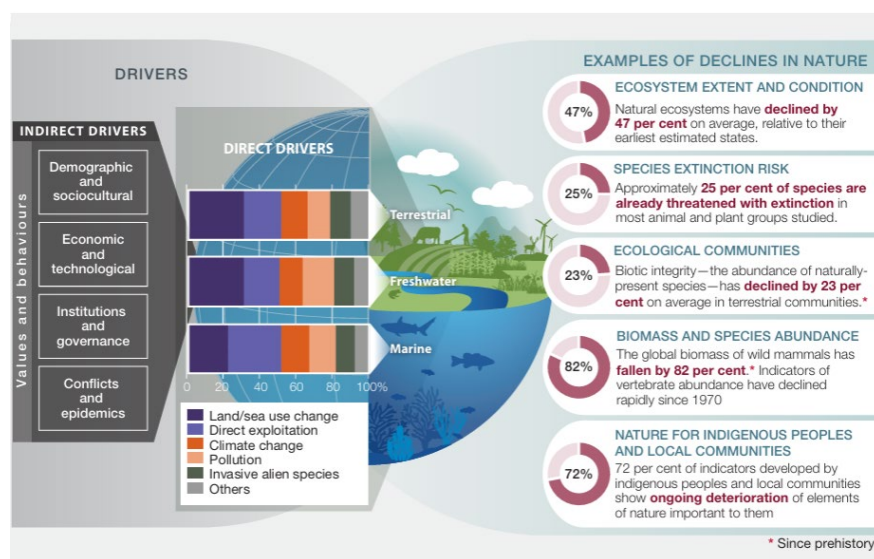


Figure 2. Drivers of biodiversity impacts (IPBES, 2019)

The IPBES further explains that climate change and pollution are the dominant drivers that accelerate biodiversity loss by altering environmental conditions beyond the tolerance limits of many species. Rising global temperatures, changing precipitation patterns and increasing frequency of extreme weather events contribute to habitat disruption. Similarly, pollution of air, soil, and water introduces chemical stressors that reduce ecosystem functioning and species survival. Further, biodiversity loss weakens the planet's regulatory abilities, including climate mitigation, creating a negative feedback loop. Ecosystems with higher biodiversity have been proven more resilient to environmental disturbances and climate change. Hence, a positive

feedback loop supporting climate mitigation is created if actions to increase diversity in our ecosystems are made (Isbell *et al.*, 2015). Studies by the IPBES (2019), indicate that restoring degraded ecosystems alone could provide up to one-third of the climate mitigation needed to keep the Earth from warming too far above pre-industrial levels.

The spread of invasive non-native species represents another major driver of biodiversity loss. Through global trade, transportation, and human movement, species are introduced into ecosystems where they may outcompete, prey upon, or introduce diseases to native species. This driver is particularly severe in ecologically sensitive regions with high levels of endemic species, such as island ecosystems. According to the UN, the number of invasive species has increased by approximately 70% since 1970 in countries with sufficient monitoring data (IPBES, 2019).

Beyond these five main drivers, several additional pressures are recognised by experts but remain insufficiently addressed in current assessment frameworks. Notably, impacts such as noise pollution and artificial light are still largely excluded from biodiversity evaluations, despite growing evidence of their ecological effects (Winter *et al.*, 2017). These gaps highlight that current representations of biodiversity drivers are not yet fully comprehensive, particularly in relation to more subtle or indirect forms of environmental disturbance that are difficult to quantify.

2.1.3 Ecosystem relationship

Understanding the relationship between biodiversity and ecosystem functioning has been a central focus of ecological research over the past 50 years, within the fields of Biodiversity and Ecosystem Functioning (BEF) and Biodiversity and Ecosystem Services (BES). Despite significant advances, the mechanisms underlying this relationship remain only partially understood (Ali, 2023). This is largely due to the complexity and context-dependency of ecosystem dynamics, which vary across spatial and temporal scales and require extensive empirical data and experiments to be fully captured.

A substantial body of research demonstrates that biodiversity plays a critical role in maintaining these ecosystem functions. Studies by Hooper *et al.* (2012) and Tilman *et al.* (2012) show that biodiversity loss have ecosystem impacts comparable to, or even greater than, other major environmental drivers such as elevated CO₂ levels. Supporting this, Cardinale *et al.* (2012) reviewed over 1,700 studies on the topic and concluded that biodiversity is a fundamental determinant of ecosystem productivity, stability, and resilience. Their synthesis shows that more diverse ecological communities are more efficient at capturing resources, producing biomass, and recycling nutrients. Tilman *et al.* (2014) more specifically found that ecosystems with “high-diversity mixtures are approximately twice as productive as monocultures of the same species.”. These effects can be explained by key ecological mechanisms. Diverse communities tend to include species with complementary traits, allowing for more efficient and complete resource use. In addition, certain ‘keystone species’ play an essential part in maintaining ecosystem processes (Ponggen, 2024). Hence, the loss of biodiversity can reduce ecosystem stability, and may disrupt trophic interactions, leading to cascading effects throughout the food web.

Overall, the evidence indicates that biodiversity is not only a characteristic of ecosystems but a fundamental determinant of their functioning and the services they provide. Declines in

biodiversity therefore have far-reaching implications to our nature, that will in turn affect the capacity to sustain human well-being.

2.2. Biodiversity in the LCA framework

A range of methods for biodiversity impact assessment has been developed, including both LCA-based approaches and so called beyond-LCA methods. However, no single method currently captures all key dimensions of biodiversity comprehensively, including drivers of loss, taxonomic groups, and ecosystem variation, due to different ecological mechanisms, spatial and temporal scales, and data requirements (Damiani et al., 2023).

Most existing methods focus either on species-level or ecosystem-level indicators, as genetic diversity typically requires laboratory-scale measurement or indirect proxies (Maier, Lindner and Francisco, 2019). This partial coverage introduces inherent trade-offs in biodiversity assessment, particularly when applied in large-scale frameworks such as LCA.

Within LCA, biodiversity loss is treated as an endpoint indicator, referred to as *ecosystem quality* or *ecosystem health*, depending on the applied method. The endpoint indicators represent the total damage from multiple environmental pressures, including land use, climate change, and pollution (Winter et al., 2017). Damage to ecosystem quality is commonly expressed in units such as species loss over time ($\text{species} \cdot \text{yr}$) or potentially disappeared fraction of species in an area, integrated over time ($\text{PDF} \cdot \text{yr}$) and sometimes also over area ($\text{PDF} \cdot \text{m}^2 \cdot \text{yr}$). Recent studies discuss complementing the PDF with Mean Species Abundance (MSA) in order to get a more comprehensive assessment as this indicator reflects changes in population sizes within a species (Kuipers *et al.*, 2025). Both indicators range from 0 to 1, where 1 reflects the biodiversity of the undisturbed reference habitat.

2.2.1 The LCA Framework

Life Cycle Assessment (LCA) is a tool that allows to quantify the potential environmental impacts of a product and organization throughout their whole life cycle; from raw material extraction to end-of-life management. As described by Hauschild and Huijbregts (2015), the general LCA framework consists of four phases according to ISO 14040:2006. (SOURCE)

1. Definition of goal and scope
2. Life cycle inventory analysis (LCI)
3. Life cycle impact assessment (LCIA)
4. Interpretation of results

In the LCI phase, elementary flow data for all inputs and outputs of the studied system is collected. In the LCIA phase, the inventory data is classified and translated into environmental impacts through the application of Characterization Factors (CF). CFs quantify the contribution of each flow to specific environmental impact categories, typically expressed at the midpoint level (e.g., climate change or eutrophication). The midpoint indicators can then be further aggregated using midpoint-to-endpoint CFs into endpoint indicators representing damage to areas of protection, including biodiversity (Eegholm, Dybdahl and Bjørn, 2025). The drivers of biodiversity loss are represented by categorizing and grouping the midpoint indicators in along certain damage pathways (Winter *et al.*, 2017). Figure 3 show the conceptual LCIA methodology to obtain biodiversity impacts. the Though, some LCIA methods bypass midpoint

indicators and directly quantify endpoint impacts, and some methods have both a midpoint and an endpoint version with separate CFs.

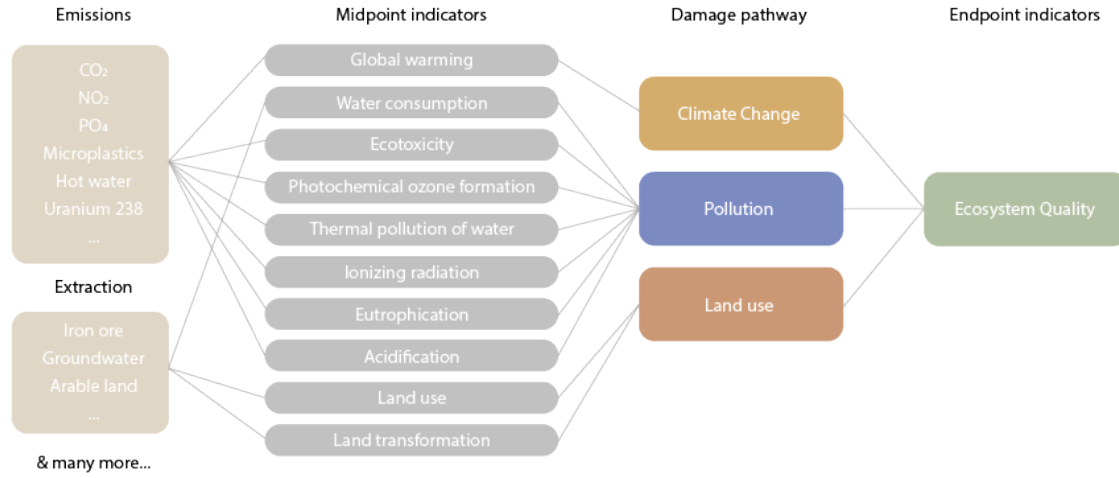


Figure 3. Life Cycle Impact Assessment methodology (Inspired by Bullet et al. (2019); ConTech Lab et al. (2026))

2.2.2 Modelling biodiversity impacts

Biodiversity loss is studied at both local, regional and global levels. The global level refers to species being extinct, while biodiversity loss on the local and regional scope does not necessarily mean that species die but they can move and continue to habitat elsewhere. To quantify biodiversity impacts within LCA, characterisation factors must be derived to link land use and other environmental pressures to biodiversity loss.

A widely applied approach to derive CFs is the *species–area relationship* (SAR) models described in a study by Chaudhary et al. (2015). The models have a simple mathematical base, measuring how species richness changes as a function of habitat area (Eq. 1).

$$S = cA^z \quad (1)$$

where S is the number of species, A is the area, and c and z are variables depending on taxonomic group and land type studied. By comparing species richness in a modified habitat to that of a natural reference state, local CFs can be defined as the fraction of species lost after the modification (Eq. 2).

$$CF_{loc,g,i,j} = 1 - \frac{S_{g,i,j}}{S_{nat,g,j}} \quad (2)$$

The factor represents the sensitivity of taxonomic group g to land use type i in region j . The local CFs are aggregated per area, and the first derivative is taken to get the regional impact as per 1m² of additional land converted within a system. First, an allocation factor is derived for the different land types i according to their relative area share p_i (Eq. 3).

$$a_i = \frac{p_i \cdot CF_{loc,i}}{\sum_k p_k \cdot CF_{loc,k}} \quad (3)$$

The occupational factor is then calculated as below (Eq. 4).

$$CF_{reg,occ} = \frac{\partial S_{lost}}{\partial A_{lost}} \cdot \frac{a_i}{p_i} \quad (4)$$

A combined regional impact factor is used in the LCIA methods, including both continuous impacts from land occupation and one-time impacts from land transformation (Eq. 5). The occupational factor is multiplied with the total land use area for all inventory flows, and the transformational factor is multiplied with total area of land use change when aggregated.

$$CF_{reg} = CF_{reg,occ} + CF_{reg,trans} \quad (5)$$

where transformation impacts are typically estimated as below (Eq. 6).

$$CF_{reg,trans} = 0.5 \cdot t \cdot CF_{reg,occ} \quad (6)$$

with t representing the regeneration time of the affected ecosystem. This method to derive CFs is used in both the classic, matrix and countryside SAR-models. The later one, though, being the most used and accounts for further details in the equation such as a species sensitivity to habitat loss, use of different habitats and the potential of species to adapt and survive in human-modified habitats which prevents overestimations. To address the global level of biodiversity impacts, a vulnerability score (VS) is added that accounts for the Global Extinction Probability (GEP) of a species. As illustrated in Figur 4, regional biodiversity impacts, which use local species richness as a baseline, may yield relatively low impact scores in biodiversity hotspots because of their inherently high levels of biodiversity. In contrast, the global perspective recognises that these hotspots contain a larger number of endemic species, resulting in substantially higher impact scores. Consequently, the regional and global perspectives may, in some cases, lead to contrasting or even opposite conclusions regarding the significance of biodiversity impacts. This discrepancy highlights the importance of transparency in biodiversity assessment methods and, more importantly, the need to consider both dimensions to provide a more holistic representation and understanding of biodiversity impacts.

Regional and global characterization factors for land

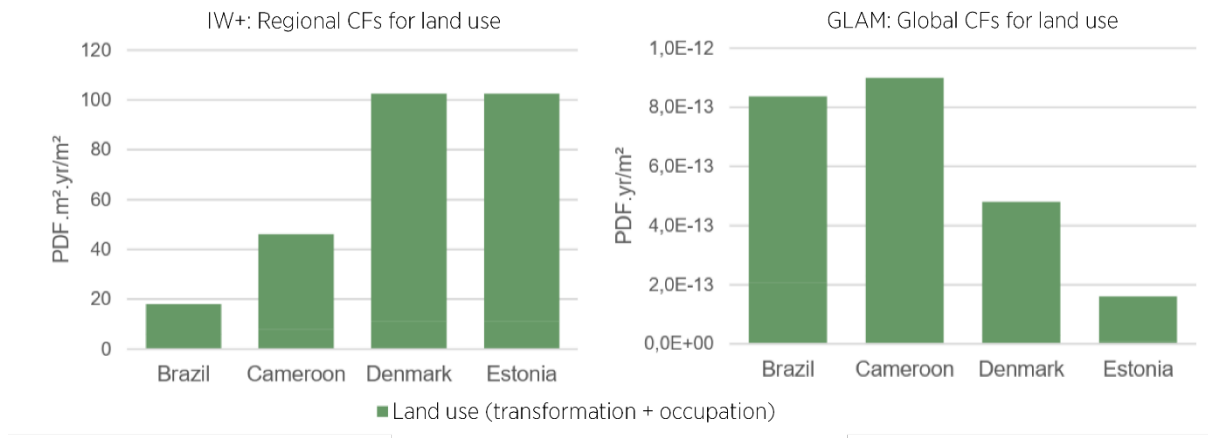


Figure 4. Comparison of average CFs for land use over a 50-year period for forestry based on IW+ (“Forest, used”) and GLAM (“Managed_forest_Intense”). Note that the two methods use different units (Strateginetværk for bæredygtigt byggeri, 2026).

An additional approach to derive biodiversity impacts in LCA is *cause–effect chain modelling*, where CFs are not directly based on ecological measures of species, but are estimated by linking emissions to potential damage to ecosystem quality through a sequence of modelling steps:

- i. **fate (FF)**, describing how a substance is distributed and persists in the environment
- ii. **exposure (XF)**, representing the contact between the affected receptor and the environmental compartment
- iii. **exposure–response (ERF)**, quantifying the relationship between exposure and a given biological or ecological effect
- iv. **severity (SF)**, translating the magnitude and duration of an effect into a damage metric

Hence, characterization factors are obtained by multiplying these factors (Eq. 7).

$$CF = FF \times XF \times ERF \times SF \quad (7)$$

This structure can be applied to most midpoint and endpoint indicators, making it easier to harmonize globally with other impact categories in LCA, though the position of the midpoint indicators varies and is category-specific (Bulle *et al.*, 2019). Compared to more detailed ecological models, which may simulate ecosystem dynamics or species-specific responses, cause–effect chain models operate at a higher level of abstraction but allow broader applicability and comparability across substances, regions, and impact pathways.

2.2.3 Background LCI data

Matching the correct database with assessment method can be a bit difficult, as it depends on the aim and scope of the analysis. Commonly used databases include ecoinvent, Sphera, and Exiobase, which differ primarily in process coverage and modelling assumptions. Among these, ecoinvent is the most recognised and widely used in LCA due to its high level of detail (Bjørn *et al.*, 2018). The ecoinvent data is offered in different system models, for example a default and a ‘cut-off’ version, describing how impacts are allocated. The default Allocation at the Point of Substitution (APOS) model allocates environmental burdens associated with recycled

materials across both primary and secondary material users. In contrast, the ‘cut-off’ version distinguishes waste from recyclable materials and assigns all upstream burdens to the primary producer. Consequently, recycled materials are considered burden-free when entering a subsequent product system, and only the impacts of collection, sorting, and recycling processes are included in the LCA (ecoinvent, 2024).

However, the recently developed BAFU:2025 database (Federal Office for the Environment, 2025) database provides a license-free alternative to ecoinvent, being the first open-source LCI database compatible with softwares such as OpenLCA. To enhance accessibility and usability, this database has been selected for further use in the study. A comparative analysis of ecoinvent and BAFU using the BBV Biotoool for timber and concrete constructions shows similar results, with deviations of +2.2% and -11.8% in $\text{PDF} \cdot \text{yr}/\text{m}^2 \cdot \text{yr}$, respectively (ConTech Lab, Sweco and Aaen, 2026). This indicates that the selected database provides results consistent with established alternatives while improving transparency and accessibility.

2.2.4 LCIA methods for biodiversity impacts

A wide range of LCIA methods exists, including ReCiPe (Huijbregts *et al.*, 2017), LC-Impact (Verones *et al.*, 2020), and Impact World+ (Bulle *et al.*, 2019), that are commonly used in LCA. However, no standardised approach for biodiversity assessment has been established, leading to variability in results due to differences in spatial resolution, taxonomic coverage, and SAR-modelling assumptions (Sanyé-Mengual *et al.*, 2022). The current LCA-based methods manage to address only three of the five primary drivers of biodiversity loss; climate change, pollution, and land use. The beyond-LCA method Product Biodiversity Footprint (PBF) extends coverage to include invasive species and overexploitation through semi-quantitative indicators as impact scores based on project specific ecological measures, such as the risk of invasive species being transported and implemented actions for species management and conservation throughout the project (Asselin *et al.*, 2020). Although, this method instead lacks detailed taxonomic resolution, highlighting the difficulty in creating a holistic method.

For biodiversity impacts, comparative studies indicate that LC-Impact and Impact World+ (IW+) provide the most comprehensive coverage among current methods implemented in softwares. Damiani *et al.* (2023) conclude that IW+ achieves the highest overall coverage among several LCA-based methods. In the context of building products, Eegholm *et al.* (2025) develops a set of conversion factors in order to compare biodiversity impacts against the planetary boundaries framework, and find that IW+ and LC-Impact agree on ranking of impacts but differ in identification of hotspots. IW+ has lower spatial resolution for some impact categories but a more balanced contribution across categories and places greater emphasis on land use impacts, whereas LC-Impact gives a higher weight to water use and eutrophication. In addition, LC-Impact’s aggregation of multiple pathways from midpoint to endpoint increase result sensitivity compared to IW+, which applies a separate version for endpoint indicators with predefined CFs. Both methods have been updated in 2026 with improved resolution and expanded impact coverage, and LC-Impact v2.0 additionally includes global biodiversity loss through GEP (Verones *et al.*, 2020).

The ongoing Global Guidance for Life Cycle Impact Assessment (GLAM) initiative is developing an updated LCIA method with a specific focus on biodiversity, which is expected to become the preferred approach once implemented in LCA softwares. The proposed CFs incorporate land-use intensity for forestry, higher spatial resolution at country or ecoregion

level, and separate treatment of taxonomic groups to better reflect biodiversity variability rather than aggregated responses (Scherer *et al.*, 2023). A general overview of the researched LCIA methods for biodiversity assessment is given in Table 1.

	LC-Impact v2.0	ReCiPe v1.08	Impact World + Expert v2.2.1	GLAM v1.0
Taxonomic groups	12/17	9/17	15/17	5/17 (separate results)
Impact categories	11	17	18	22
Categories addressing biodiversity	8	9	13	9
Categories spatial resolution	High	Low - Medium	Medium - High	Very high
Biodiversity modelling	c-SAR	Simplified SAR	Cause-effect	c-SAR
Spatial level	Local loss + Global extinction	Local loss	Local loss	Local loss + Global Extinction
Geographic resolution	Native, ecoregion, country, global	Country, continent, global	Native, ecoregion, country, continent, global	Ecoregion (biome), country, global
Latest update	2026	2016	2026	2024 (not in softwares)
Midpoint impacts	No	Yes	Yes (separate CFs)	Yes (separate CFs)
Endpoint impacts	Yes	Yes	Yes	Yes
Unit	PDF.yr	Species.yr	PDF.m ² .yr	PDF. m ² .yr
Land types	6	6	6	5
Country-specific CFs	Yes	No	Yes	Yes
Land use intensity levels	Intensive, Extensive	Intensive	Intensive	Minimal, light, intense

Table 1. Overview of the researched LCIA methods

2.3 Integrating biodiversity impacts in building LCA

In the building sector, Environmental Product Declarations (EPDs) are commonly used as data sources for building LCAs, providing pre-calculated environmental impact data for building products which simplify the LCI and LCIA phases. As a result, the basis of most building LCA softwares is simplified to multiplying the declared unit of each building materials by its emission factor from the EPDs (Hollberg, 2016). The developed standard EN 15978/EN 15804 for building life cycle assessment is divided into five main stages as shown in Figure 5.

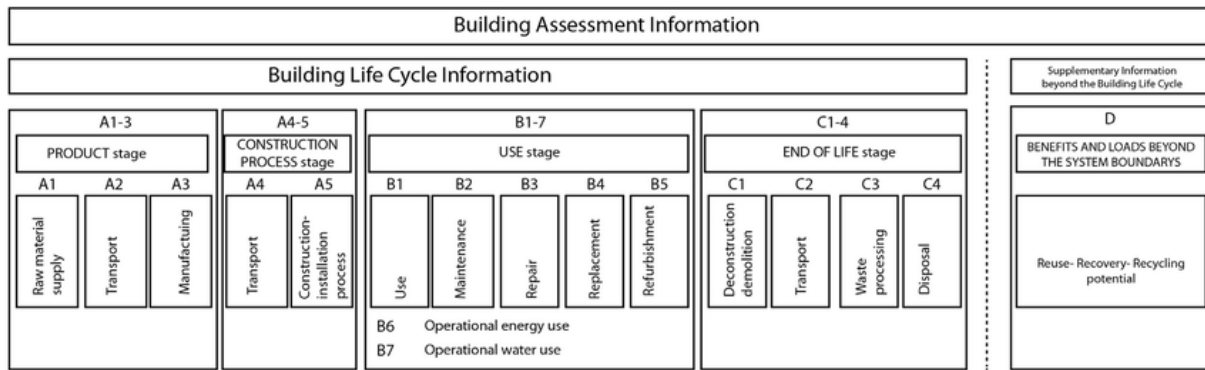


Figure 5. Life cycle modules (EN 15978:2012)

2.3.1 The potential of EPDs

The EPDs include several environmental indicators, but not yet biodiversity impacts. Though, they contain many of the midpoint categories relevant to biodiversity assessment, such as climate impact and pollution, which can theoretically be converted into biodiversity impacts using midpoint-to-endpoint CFs. However, the approach is associated with substantial uncertainty due to inconsistencies in the underlying models and assumptions (Upstream Partners *et al.*, 2025). Moreover, several EPD impact categories require unit conversions before they can be meaningfully linked to midpoint-to-endpoint CFs. Although conversion factors across LCIA methods have been proposed (Dong *et al.*, 2021), these efforts also demonstrate significant methodological limitations and challenges in achieving harmonisation. In addition, current EPD standards do not include requirements for reporting land use and land-use change, despite its importance as a key driver of biodiversity impacts in the built environment, which likely results in a considerable underestimation of total impacts. If EPD standards were expanded to include land use, or ideally to incorporate biodiversity impact as an endpoint indicator, this would represent an important step toward broader availability of both product-specific and publicly accessible generic environmental data on biodiversity impacts.

2.3.2 Current methodologies

As building LCA practice relies on EPD databases, biodiversity impacts must currently be added as an additional step using supplementary tools that extend conventional LCA outputs to include biodiversity indicators. Among the few user-oriented tools available for this purpose are the Doughnut Biotoool (Francart, 2024) and the BBV Biotoool (Sweco and Aaen Engineering, 2025). The Doughnut Biotoool was the first to be released, while the more recent BBV Biotoool builds on a similar methodological foundation and structure but introduces additional details such as more detailed sourcing options for bio-based materials. Both tools are Excel-based and apply an attributional LCA framework.

The tools use a backtracking approach to estimate biodiversity impacts for building projects by mapping and categorising the building materials from the LCA result sheets and extracting the corresponding material quantities. The building materials are grouped into broader material categories and subsequently linked to corresponding generic processes in a life cycle inventory database, covering both production and end-of-life stages. For instance, a specific product such as ROCKWOOL Conlit Fire Board EI90/EI120 belongs to the group “insulation” and is

mapped to the generic category “stone wool insulation”, which corresponds to the processes “rock wool, at plant – CH” for the product stage (A1–A3) and “disposal of mineral thermal insulation as building waste – CH” for the end-of-life stage (C3–C4). The replacement impact (B4) is determined based on the product lifetime relative to the overall study period. Further, values for on-site impacts (A4-A5) can be calculated through adding user inputs on land type data for the project site. Selection of country and forestry practice for the bio-based materials can also be manually adjusted for sensitivity analyses, with a default set to global averages.

In the updated BBV Biotool, users can manually create and modify mappings of building products. However, the initial database is based on pre-existing mappings of materials available in LCAbg. Consequently, the tool can be used with LCA results from other softwares as well, although this requires manual mapping. The biodiversity impacts of the generic processes are pre-calculated, using openLCA and the IW+ method for the BBV Biotool, which was selected by the developers due to its relatively conservative treatment of land-use impacts, identified as a key driver of biodiversity loss. The results are calculated and visualized in the tool, and further analysis can be made, displaying contributions per building component, per life cycle stage and per material group with details on midpoint impact contributions grouped in the three drivers; climate change, land use and pollution. Figure 6 shows the main results sheet in the BBV Biotool, as well as the material mapping, and the resulting graphs generated in the tool.

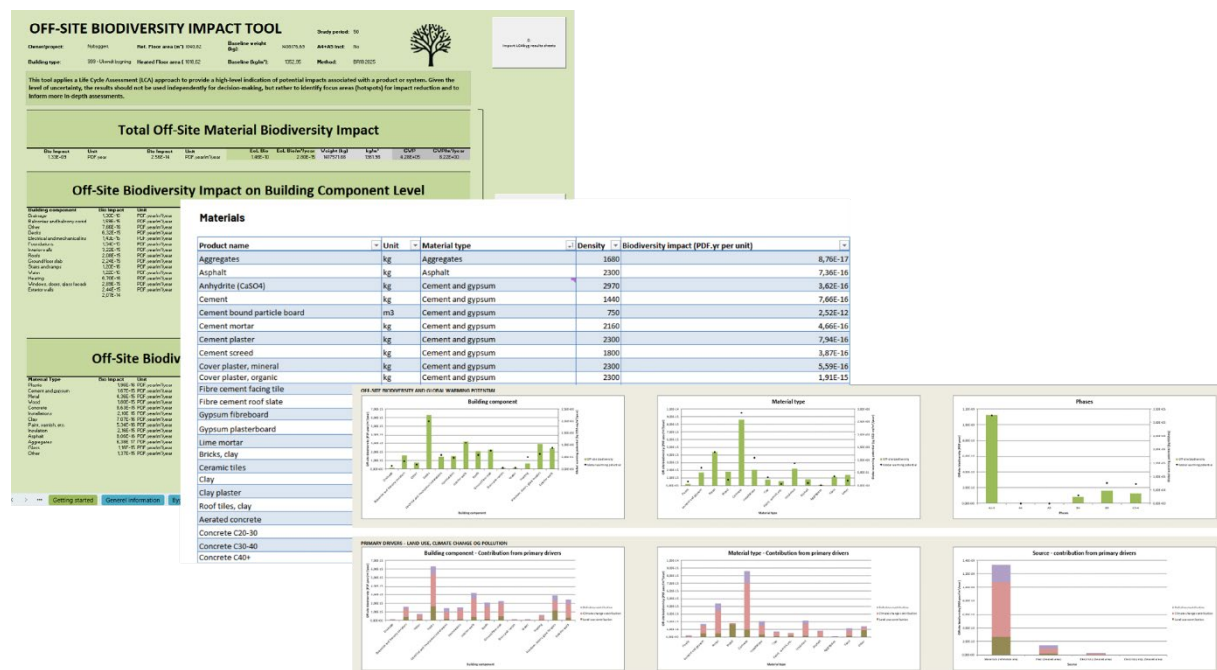


Figure 6. Overview of the BBV Biotool interface

2.3.2 A regionalized approach

As shown in Figure 7 biodiversity impacts in building LCA terms is split in off-site and on-site impacts, where the largest impacts lies in the extraction and production of materials. In the use phase, the land of the building site is accounted for as well as operational energy where

countries with high portions of biogas in their energy mixes will have higher impacts. The end-of-life management is often landfill, incineration or recycling which is also accounted for in the off-site impacts.

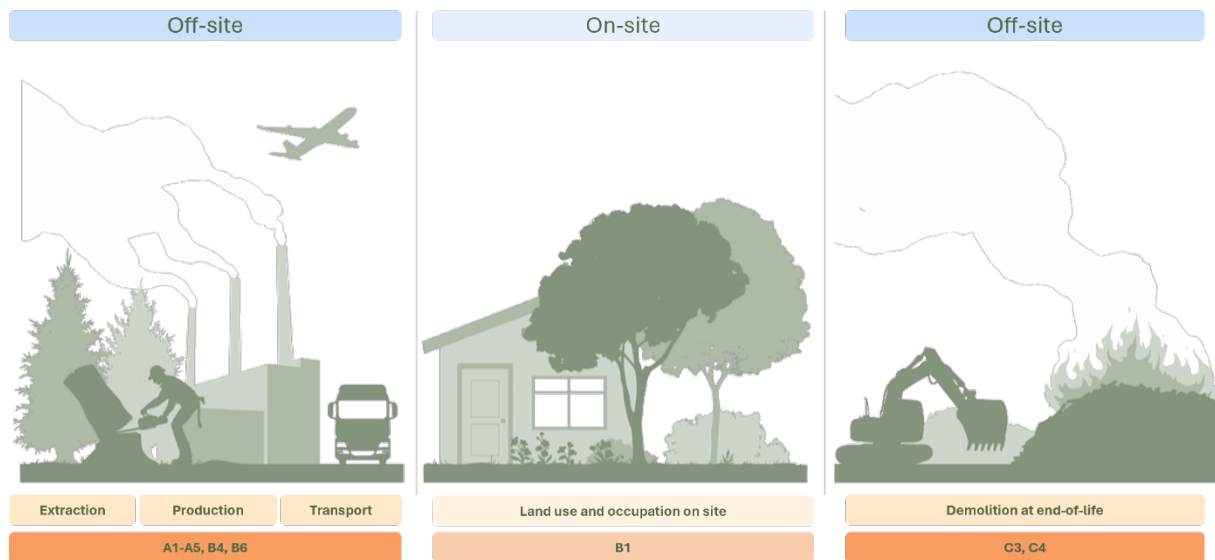


Figure 7. Off-site and on-site biodiversity impacts (Adapted from BBV (2025))

Compared to GWP, where the outlet impact is set against global benchmarks, biodiversity impacts are highly location dependant. A timber product sourced from the Amazon forest will for example have a lot higher impact than the same tree sourced from Denmark. It also depends a lot on land use intensity such as forest management. Data derived from the GLAM project with the global intensive forestry as a baseline of 100% show that extensive forestry reduces impacts by about half. For Denmark, intensive forestry is around 27% and from Sweden it's 5% compared to global values (ConTech Lab, Sweco and Aaen, 2026). The results shows a substantial difference in impacts depending on land use management, and there are mixed opinions on land sharing or land sparing strategies for agriculture and forestry amongst experts, as extensive forestry also mean a larger area will have to be converted to uphold the same demand but have higher natural biodiversity whereas land sparing aims maximize a smaller land area and leave as much as possible for natural vegetation.

2.3.3 Challenges and Uncertainties

Life cycle assessment (LCA) is inherently associated with several uncertainties related to methodological choices, assumptions, and data limitations. Although ISO standards provide a general framework for conducting LCAs, practitioners still decide system boundaries, allocation procedures, databases, and LCIA methods. These choices influence the results and can lead to variation between studies assessing the same building or product system. In building LCAs, product-specific EPDs are preferred, but generic average values are often used when specific data are unavailable. Since generic datasets may not accurately reflect actual production conditions, this introduces additional uncertainty. In general, LCA results should not be seen as absolute environmental impact measure but a predicted impact of a system (Hollberg, 2016).

The evaluation of biodiversity impacts introduces additional layers of complexity. Biodiversity measures rely on project-specific ecological analyses, which are rarely feasible in building projects due to economic and practical constraints. As a result, biodiversity assessments in LCA rely heavily on generic characterization models and inventory data that are often non-spatially explicit and insufficiently representative of local ecological conditions. Bromwich *et al.* (2025) categorize uncertainties of biodiversity assessment in LCA into three main groups: epistemic, linguistic, and decision-based uncertainties. Epistemic uncertainty relates to incomplete scientific knowledge and limitations in data or models. Linguistic uncertainty concerns the interpretation of biodiversity indicators and terminology such as the potentially disappeared fraction of species. Decision-based uncertainty originates from methodological choices including system boundaries, databases and LCIA methods.

The level of uncertainty increase with the scaling of impacts along the damage pathway, moving from midpoint to endpoint impacts (Bromwich *et al.*, 2025). This process simplifies complex ecological relationships into aggregated metrics representing potential biodiversity loss. The complexity of ecosystems are poorly represented as most impact methods assume additive relationships between pressures, whereas in reality ecological response are nonlinear and affected by a network of interactions (Tilman, Isbell and Cowles, 2014). In addition, current LCIA methods do not cover all levels and pressures of biodiversity, and comparing them is difficult due to their difference in fundamental structure, impact indicators and units (Eegholm, Dybdahl and Bjørn, 2025). Characterization factors (CFs) applied in the LCIA methods to weigh impacts also adds uncertainty as they are often based on highly aggregated global datasets with limited regional specificity due to lack of data availability. Widely used land-use CFs developed by Chaudary and Brooks (2018) have, for example, been criticized for poor representation of urban areas and regions with high conservation value (Martin, Green and Balmford, 2019).

In the building sector, the uncertainty of biodiversity footprints is further reinforced by limited supply-chain transparency and the lack of biodiversity indicators in most product EPDs, causing a need to fall back on generic data. However, the lack of spatially explicit data for elementary flows in current LCI databases is a major issue where these often represent broad geographic scopes such as global (GLO) or European (RER) averages, which limits the location specificity of biodiversity assessments and reduces its ability to reflect local ecological conditions accurately. There is therefore a clear need for further research to improve biodiversity assessment methods in LCA, particularly through more comprehensive impact categories, improved regionalization, and higher-resolution inventory data.

Despite these limitations, biodiversity LCAs remain valuable as high-level screening tools for identifying impact hotspots, prioritizing materials and processes, provided that uncertainties are transparently communicated (Bromwich *et al.*, 2025). Recognizing the risks associated with uncertainties and balancing them against the costs of both inappropriate action and inaction, is essential for developing effective biodiversity strategies. Decisions and biodiversity strategies should not rely solely on LCA impact results but should if possible be complemented with other analyses to form resilient actions that collectively support a nature-positive future.

This study does not attempt to resolve the methodological limitations of current biodiversity assessment methods in LCA. Instead, it explores how biodiversity indicators can be operationalized in practice, and how it may evolve as improved data and methods become

available. In particular, the study investigates how biodiversity and climate change impacts together may inform building design decisions.

2.4 The architectural design process

The architectural design process is iterative and varies across offices, influenced by internal practices, design approaches, and project priorities. In wide terms, it is commonly structured in four main stages: Concept Design (CD), Schematic Design (SD) and Detailed Design (DD).

The process begins with analysing site conditions, context, users, and project goals to establish a clear problem framing. During CD, initial zoning and massing studies are explored, resulting in a defined design concept with overarching goals and an architectural language. In SD, the concept is further developed through volume studies of design options, supported by physical modelmaking and computational analyses of e.g. structure, daylight, and material considerations. Later, the main features of the building project is set and drawings are developed more in detail along with visual communications and iterating the layout to meet all requirements. The DD phase refines the project in detail, integrating technical requirements and producing more precise drawings and documentation needed to begin construction. This general structure aligns with descriptions by Hettithanthri et al (2023).

2.4.1 LCA in the workflow

Sustainability is becoming an increasingly important aspect of architectural practice, driven by certification schemes, client requirements, and emerging climate regulations. In Denmark, LCA documentation became mandatory in 2025 with an average allowed limit of 7.1 kg CO₂e/m²/year for new building projects, depending on type and size, being a sign in the right direction (BR25). Though, sustainability inputs often remain advisory rather than fully integrated into design decision-making. Architecture firms employing in-house experts have easier access to specialist throughout the design process, while others relying on external consultants might not get the same level of expert inputs.

The LCAs are typically conducted in later design stages when detailed product data is available. Here, opportunities for major design changes are limited at this point, and efforts focus primarily on optimisation and specific product selections amongst EPDs. At CF Møller Architects, early-stage CO₂ estimations are supported through an in-house Grasshopper–Rhino tool based on geometric assumptions. However, such approaches are not consistently applied across projects, and there is an ambition to strengthen sustainability competencies among architects to better integrate environmental considerations throughout the design process.

2.4.2 Gaps and opportunities

While sustainability and life cycle thinking are increasingly present in contemporary practice, quantified measures are typically introduced in the later stages where design decisions are already largely defined and is often dependent on the availability of detailed information and external expertise. This design paradox is illustrated in Figure 8.

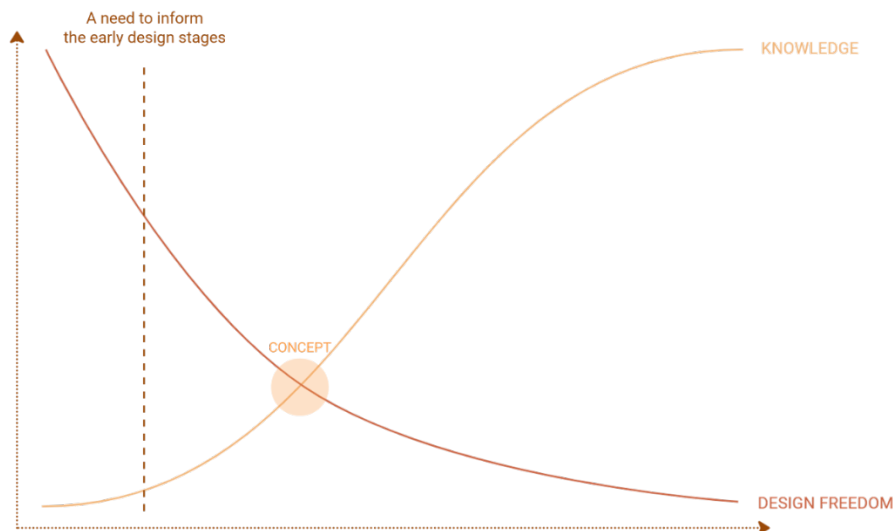


Figure 8. The design paradox (Adapted from Ullman, 2010)

Both literature and practice highlight a general need to inform the early-stages of the design process (Ullman, 2010; Francart, 2024). These phases have the greatest influence on a project's costs and environmental performance, while also offering the highest potential for optimisation due to the low cost of design changes. However, they are characterised by limited and uncertain information, whereas the detailed data required for comprehensive LCA becomes available only in later stages, when design changes are significantly more difficult to implement (Hollberg, 2017). This creates a mismatch between when decisions have the greatest impact and when environmental assessment tools can effectively support them.

At the same time, the architectural design process is highly iterative, involving continuous exploration of alternatives through spatial, formal, and technical studies. However, environmental and material-related feedback is not consistently embedded in these iterations. This creates a disconnect between design exploration and environmental performance evaluation, where decisions with significant long-term impact are made without integrated feedback on their consequences.

From a practice perspective, similar challenges are evident. Interviews and workshops with architects indicate a need for tools that can support early volumetric studies through fast and intuitive feedback mechanisms (Rodríguez-Álvarez and Gonçalves, 2020). At CF Møller Architects, there is a clear ambition to integrate sustainability earlier in the design process and to strengthen awareness among architects when designing. The aim is to influence decision-making continuously, which can be supported by accessible tools that allow exploration of environmental impacts in relation to geometry and design variations. through an intuitive tool that allow practitioners to explore environmental impacts in relation to geometry and design variations. In this context, simplicity and usability are emphasised as critical factors, as time constraints and varying levels of expertise require interfaces that remain readable and accessible to non-specialists.

These observations are supported by research, showing that visual and computational tools can enhance the iterative and exploratory nature of early design processes, which are often driven by volume studies and scenario-based approaches (Purup and Petersen, 2020; Kamari *et al.*,

2021). This highlights an opportunity for parametric design tools that connect geometric models with quantitative indicators such as global warming potential and biodiversity impact, providing the flexibility and interactivity needed to operate within the creative nature of early design work.

2.4.3 Implications to this project

Based on the identified gaps, this thesis develops a digital design tool positioned in the early design stages, specifically useful in CD and SD. The tool is intended to support rapid, iterative design studies by linking geometric form generation with simplified assessments of global warming and biodiversity impacts.

3. Methodology

The following section introduces the methodology of the thesis. Firstly, the review of literature and design projects, followed by a description of the interviews and workshops. Secondly, the framework for the digital tool is described and the case studies are presented. Figure 9 shows the main methodologies in relation to the research questions.

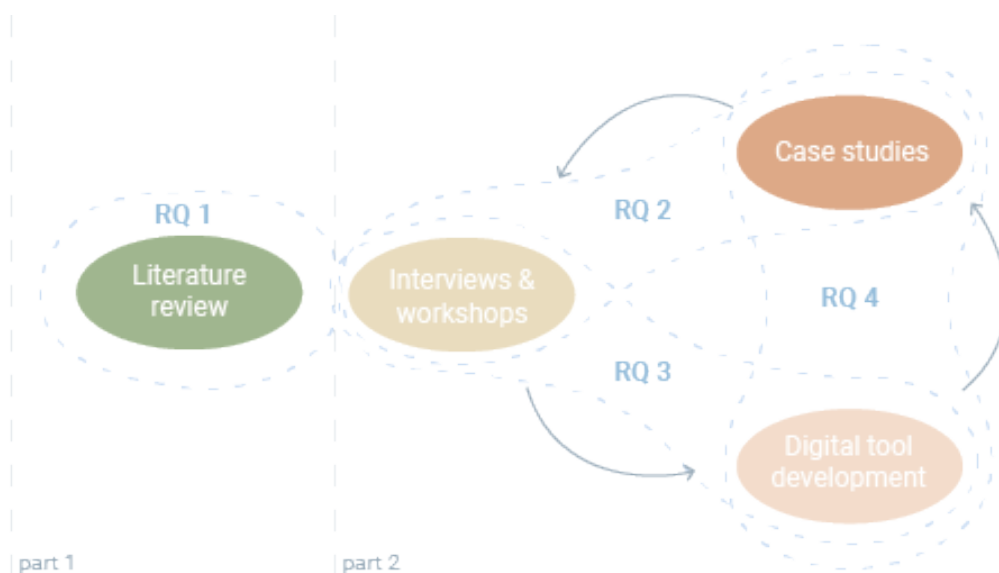


Figure 9. The main methods and the connection to research questions

3.1 Literature review

A literature review was conducted to examine methods for biodiversity assessment in LCA and to position the study within existing research. The review also aimed to evaluate the potential for implementation in industrial practice through an analysis of the architectural design process, and to identify key sources of uncertainty.

3.2 Design project reviews

To gain a deeper understanding of the architectural design process, project documentation from different design phases of several projects by CF Møller Architects was reviewed. This was supplemented by an analysis of project submissions from previous professional experience in the architectural field.

3.3 Interviews and workshops

To investigate how biodiversity assessment can be best applied in practice, semi-structured interviews were conducted with members of the sustainability team at CF Møller Architects. The interviews focused on the design process of building projects with high sustainability ambitions, and the interdisciplinary collaboration between architects and sustainability engineers. Particular attention was given to the potential integration of biodiversity assessment methods in existing design strategies and tools.

In addition, participation in a workshop was undertaken together with CF Møller Architects. The workshop was organized by Sweco, Aaen Engineering, Molio and ConTech Lab as part of the BBV project. It focused on the practical implementation of the new version of the biodiversity assessment tool *BBV Biotool v.1.1.2*, including its methodology and interpretation of results.

3.4 Digital tool development

This chapter describes the development of the digital design tool, including system boundaries, the construction of a database and its integration with architectural volume models. The methodology outlines how material-specific data from building LCA software is linked to generic datasets with corresponding biodiversity impacts. The resulting tool combines GWP values from the performed LCA with added biodiversity impacts, which are interactively updated based on the design geometry in Rhinoceros. Figure 10 shows the conceptual methodology of the tool.

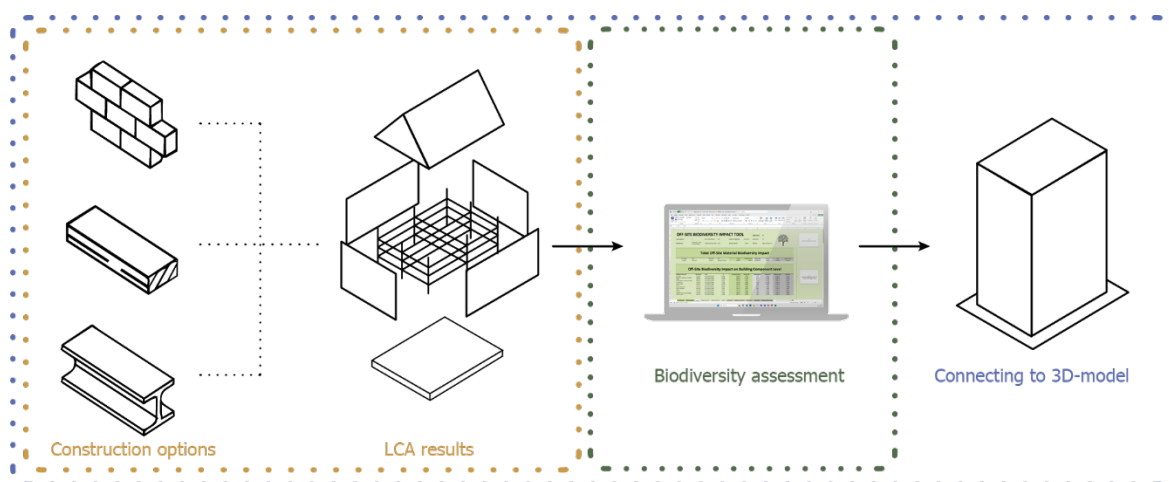


Figure 11. Conceptual methodology of the developed tool

3.4.1 System boundaries

The tool covers off-site biodiversity aspects of materials only, thereby including production stage A1-A3, replacements B4 and end-of-life management C3-C4. A reference service life of 50 years and a reference area of 1 m² have been used for all constructions. The functional unit (FU) differs between the assessed constructions and is defined either per square metre (m²) or per linear metre (m). The biodiversity impact calculations utilize the Biotoool BBV v1.1.2 that is based on the BAFU:2025 Database. and use the LCIA-method IW+ Expert v.2.0.1. The unit conversion from [PDF.m².yr] to [PDF.yr] is conducted according to the method by Weidema, B.P. (2015). The percentage reductions in land-use impacts for bio-based materials sourced from specific countries and forestry management practices are relative to global values, and based on GLAM.

The impact categories included from the LCA results of the constructions was limited to climate impact in the form of GWP with the unit of kg CO₂e, to keep the focus on biodiversity impacts. The building components studied are categorized to match the selection of constructions from the database and limited to load-bearing elements, walls and the building envelope. Figure 12 shows the building components included in the tool.

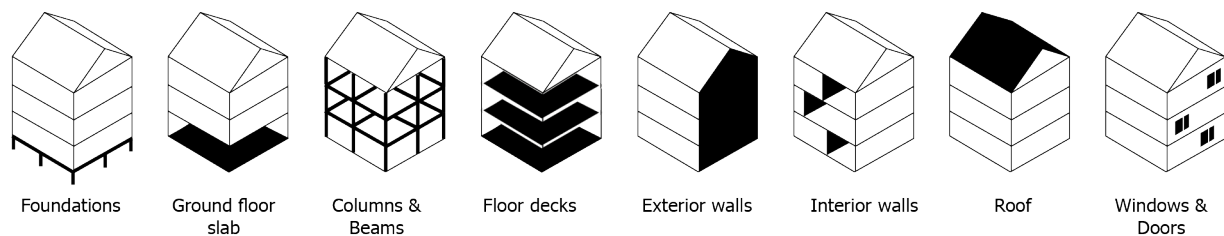


Figure 12. Building components included in the tool

Mapping of the building products to generic data in order to estimate the biodiversity impacts, are done using below generic material types according to the BBV Biotoool, with further sub-selections of more specific products under each type.

- Aggregates
- Asphalt
- Cement and gypsum
- Clay
- Concrete
- Electricity
- Glass
- Heat
- Installations
- Insulation
- Metal
- Other
- Composite
- Green roof
- Paint, varnish, etc.
- Plastic

- Stone and masonry (other than clay)
- Other biobased materials
- Wood
- Transport

The geographical scope of the tool is by default global, with the option to including weighting factors for country-specific sourcing of biobased building products which will affect the impacts stemming from land use of said product. The factors are available both for extensive and intensive forestry (see Appendix II). As the tool is aimed for use in the Scandinavian context, the below countries are included as well as an option in line with the European market for biobased products:

- Denmark
- Sweden
- Norway
- Germany
- Estonia
- Finland
- Latvia
- Poland
- Market-based (Europe)

3.4.2 Constructing a database

To obtain material-specific data for the biodiversity assessment, a library of constructions was developed containing information on material quantities and GWP. This catalogue was built using pre-defined construction layers in the software LCAbyg, containing data from mainly EPD Denmark. Inside the software, each building component is defined through a simplified structure consisting of an outer layer, a middle layer, and an inner layer that together form a complete construction (see Figure 13). Through exporting the LCA results of all construction layers for a set unit, the material quantities and corresponding impacts of the construction layers can be extracted. This information forms the foundation of the database, which is used for the biodiversity impact estimations and further linked to geometric quantities. The full database can be found in Appendix I.

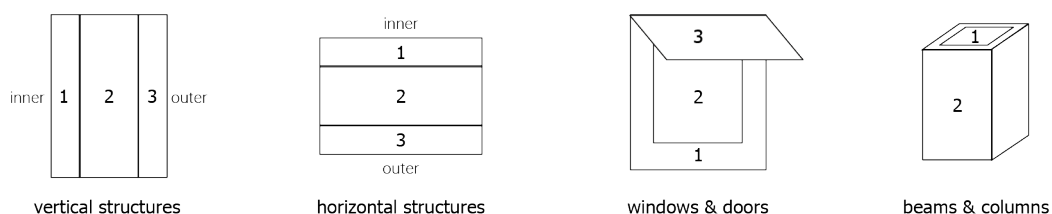


Figure 13. The construction layers forming a complete building component

3.3.3 Calculating impacts

The biodiversity footprint (BF) of all materials in each construction layer was calculated using the BBV Biotoool, in which the result sheet from LCAbyg was imported to obtain the material

types and quantities. The tool then calculates biodiversity impacts for each individual building material within the assemblies. To derive impacts at construction-layer level, additional summarising calculations were performed in Excel. The final database includes biodiversity impacts per building material and per construction layer, as well as the contributing drivers and the distribution across life cycle stages. The corresponding GWP impacts were extracted directly from the LCA software, calculated using generic datasets. The reported values represent total GWP. Biogenic carbon uptake is accounted for in the product stage (A1–A3), while an equivalent emission is assumed in the end-of-life stages (C3–C4) due to incineration, resulting in a net-zero balance of biogenic carbon across the life cycle. As a result, the reported total GWP effectively reflects fossil GWP only.

3.4.4 Connecting the database to design geometry

A computational script was developed in Grasshopper using Python-based components to link the constructed database with early-stage architectural models in Rhinoceros. The workflow operates on volumetric design models and translates these into simplified representations of building components such as walls, slabs, and roofs based on predefined assumptions and project-specific parameters. Further, the user assigns construction assemblies from the database to each building component inside the script. The environmental performance is then calculated by combining geometric quantities with the corresponding data from the selected construction layers, generating results for both GWP and BF.

Additional components allow for adjustments of biodiversity-related parameters, including forestry management scenarios and geographic weighting based on the origin of bio-based materials (country-specific or market-based). These parameter values are derived from the BBV Bioutil, but origins from GLAM. By default, calculations are based on global average values.

3.5 Case-studies

A series of case studies was conducted to investigate the value of including biodiversity assessment in building design practice together with GWP, and how the developed tool can inform early decision-making. The studies are presented below.

3.5.1 Green Hub House

Green Hub House is a multi-storey housing project that started to be built in 2023, and expected to be finished in 2027, with a total Gross Floor Area (GFA) of 4000m². It is located in Aarhus, Denmark and consists of two building volumes with prefabricated timber modules, reused façade panels and reclaimed hollow-core slabs. A render of the envisioned project is shown in Figure 14.



Figure 14. Rendered view of Green Hub House (CF Møller Architects)

The project is selected due to its high focus on implementing strategies for decarbonization. To investigate potential trade-offs with low-carbon strategies in relation to biodiversity impacts, the project was assessed and analysed using the BBV Biotoool.

Green Hub House is developed as a demonstration project under the initiative *Boligbyggeri fra 4 til 1 Planet*, aiming to establish new standards for sustainability, with a documented target of reducing CO₂e by 75%. It's a residential development combining 47 housing units, shared facilities, and commercial spaces within an experimental framework for climate-conscious construction. To achieve the low carbon footprint of 3,2 CO₂e/m²/yr three main strategies have been applied.

- Timber frame construction with screw fundamentals
- Recycled materials for façade, ground floor slabs and floor decks
- Focus on energy and indoor climate

3.5.2 Balance Boliger

The second case study is based on the research project, *Balance Boliger*, by CF Møller investigating the climate impacts of six typical build-ups for classic Danish residential housings and strategies to reduce the carbon footprints, put into context of the new Danish climate regulations, BR18, and the implication for green building certification scheme DGNB. This study explores the biodiversity impact of each scenario and their respective sensitivity to country-specific sourcing of bio-based materials. The project is also used for verifying the results from the developed design tool, due to the ability to compare different structural systems. The residential module used in the *Balance Boliger* project have the dimensions of 16.1 x 11.8 x 17.4 m (H x W x L), with a total GFA of 1026m² distributed over five floors. Figure 15 shows drawings and images of the residential module and Figure 16 displays the studied structural systems more in detail.

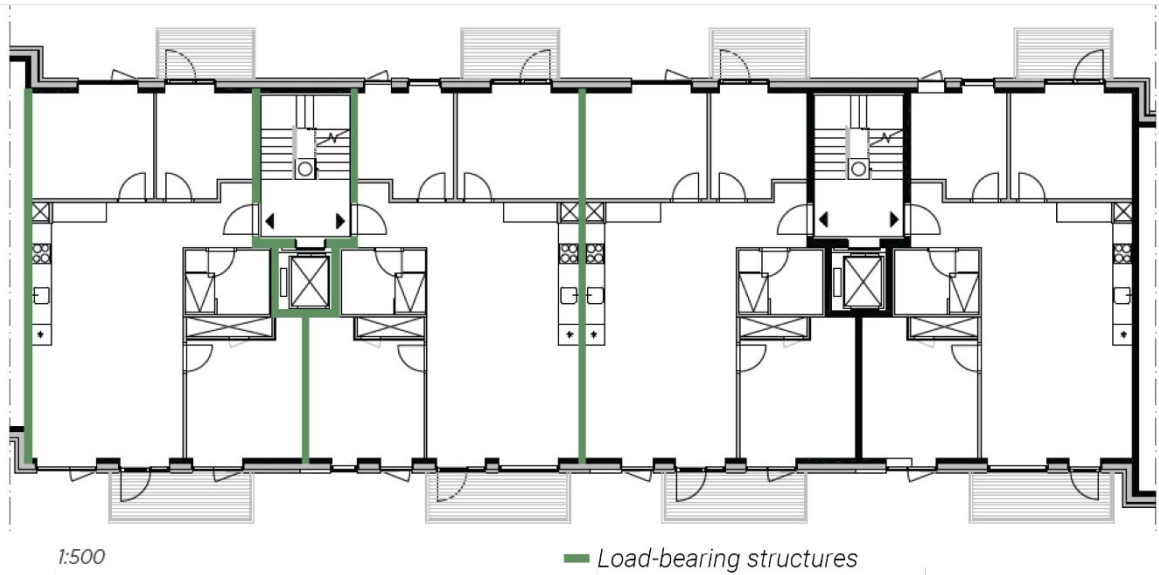
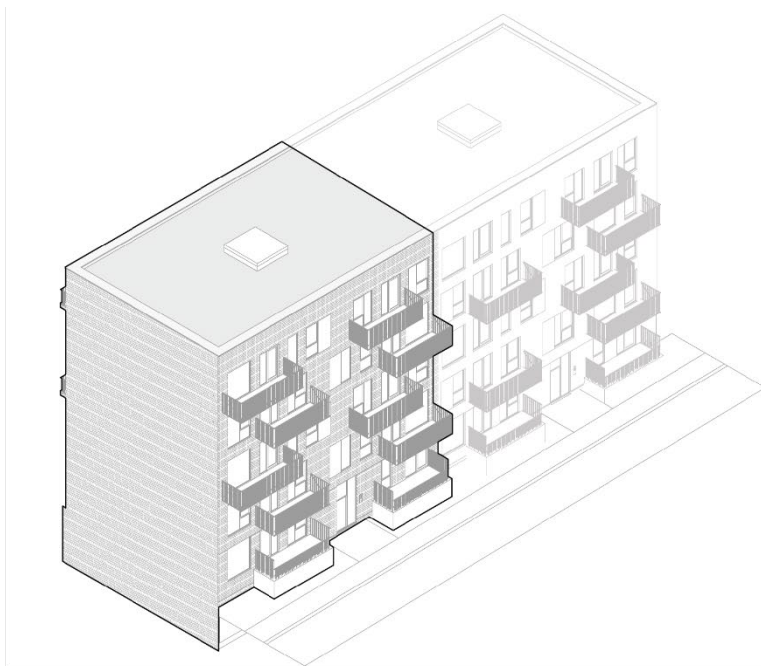
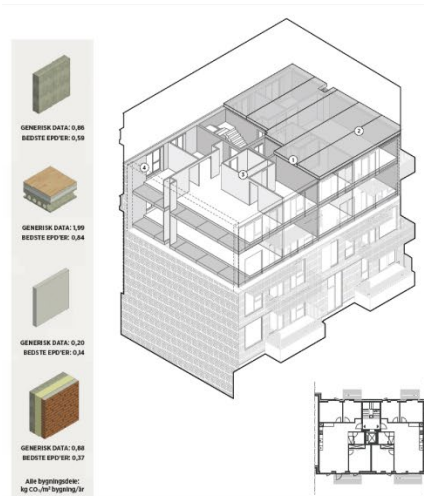
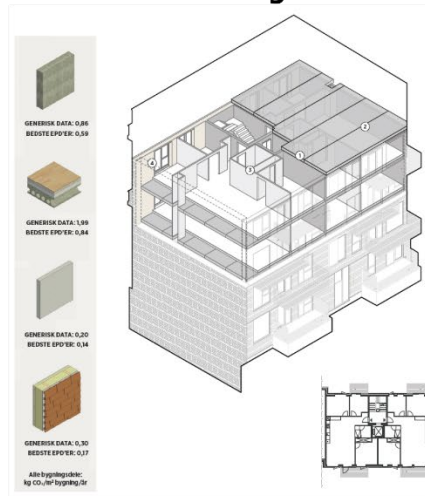


Figure 15. Drawings and images of the residential module used in Balance Boliger (CF Møller Architects)

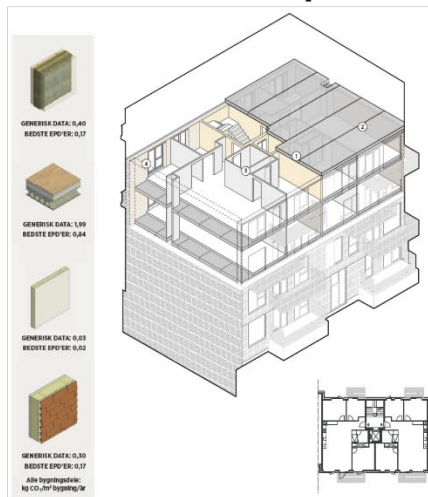
1. Traditional concrete



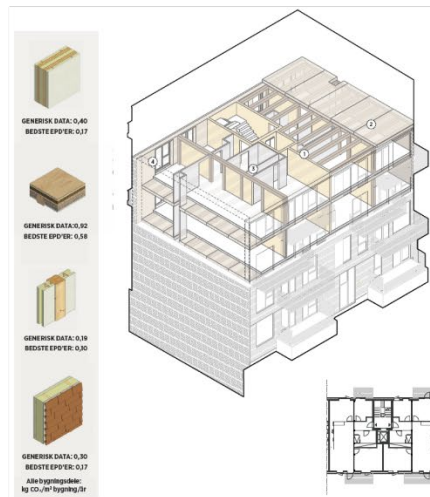
2. Concrete with light facade



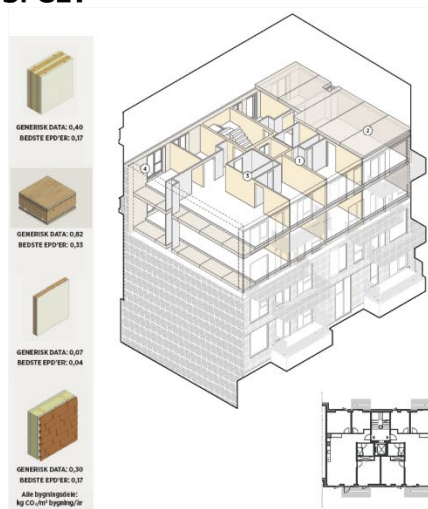
3. Timber/concrete hybrid



4. Timber beams & columns



5. CLT



6. Prefabricated timber modules

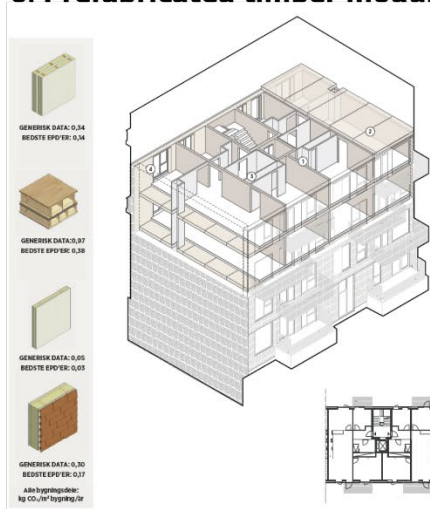


Figure 16. The structural systems investigated in the project (CF Møller Architects)

3.5.3 Fælledby school

The school in Fælledby is an ongoing project by CF Møller, currently in its later stages, and has been selected as it reflects a typical architectural design process. This case study uses some of the documented design studies throughout the process to demonstrate how the developed tool can be applied in practice and the type of information it can provide. Volume models from early massing studies are assessed in terms of global warming potential and biodiversity footprint using the tool, with results presented at a total building scale to suit the level of interest at this point. In addition, a more detailed 3D model of the school, including built geometries for interior walls, is used to illustrate the tool's relevance in later early-stage design, where more detailed assessment results on construction-level could be of interest.

3.5.4 Benchmarks

To evaluate and compare biodiversity impacts from the case studies, the proposed baseline-values from the BBV project is used (Upstream Partners *et al.*, 2025). The baseline values are based on the median of the assessed 50 case studies in the project. The suggested baseline values combine bottom-up reduction estimates with top-down thresholds derived from scientifically established biodiversity limits, including the Planetary Boundaries framework (Richardson *et al.*, 2023). While methodologies for allocating the biosphere integrity boundary remain under development, these values provide a science-informed basis for defining reduction pathways. The baseline values are shown in Table 2.

	Materials	Drift	All phases
	A1-A3, B4, C3-C4	B6	A1-A3, B4, B6 C3-C4
Lower quartile	3,0 E-14	0,7 E-14	3,9 E-14
Median	3,5 E-14	0,9 E-14	4,3 E-14
Upper quartile	4,0 E-14	1,0 E-14	5,2 E-14

Table 2. Suggested bottom-up baseline values in the BBV project (PDF.yr/m² building/yr)

4. Results

This chapter presents the main findings of the thesis. The first part describes the intended placement of the tool in the design workflow, drawing on interviews with CF Møller Architects, relevant literature and prior professional experience.

The second part focuses on the development of the digital design tool and its application in case studies, examining how it can support decision-making across different types of design studies and how its results can be interpreted.

4.1 Placement in the workflow

At CF Møller, integrating LCA measures continuously is a key part of the overall sustainability strategy. Their developed workflow begins in the planning phase, where LCA strategies are established as a part of each project's sustainability framework. Throughout concept development and detailing, a range of tools are applied for screening and variant studies of components, progressing from early indicative LCA calculations to more detailed assessments. In the delivery phase, final LCA calculations are carried out using dedicated software. The biodiversity design tool developed in this project is intended to align with this workflow, as shown in Figure 17. The primary target is the early screening phase, where rough total impacts of massing alternatives can be evaluated, as well as the later concept phase, where increased details in the assessment results may be useful for hotspot analysis as the 3D models become more developed. In addition, constructing a biodiversity database of constructions can support more detailed material analysis of specific building components for variant studies to address the remaining two steps in the workflow of conceptual design, though not the main focus.

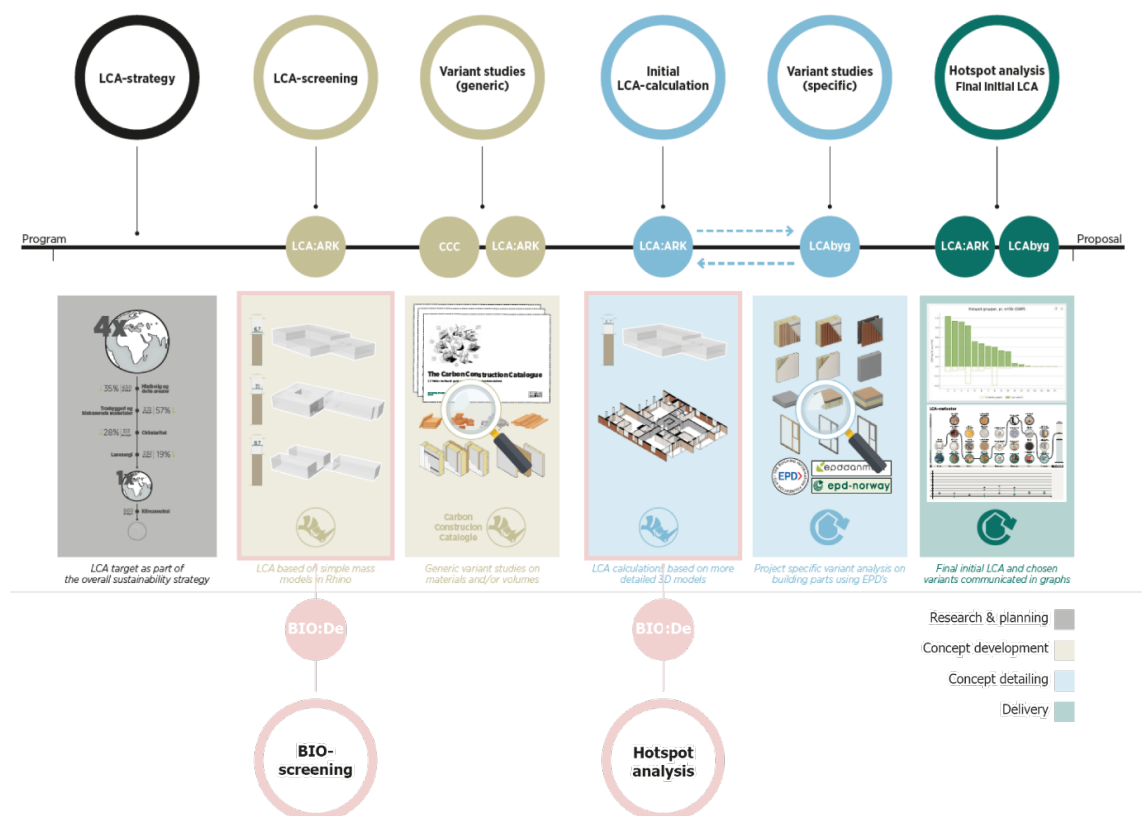


Figure 17. The developed tool (pink) in the LCA workflow at CF Møller. (Adapted from CF Møller Architects)

4.2 Digital tool framework

In this chapter, the developed tool and methodology behind it is presented. To enhance simplicity and increase the usability of the tool for non-experts, the Grasshopper-script consists of four main components that are coded in Python. The components generate geometry, calculate and adds country-specific weighting of biobased materials. Figure 18 shows the overall functional framework of the developed tool.

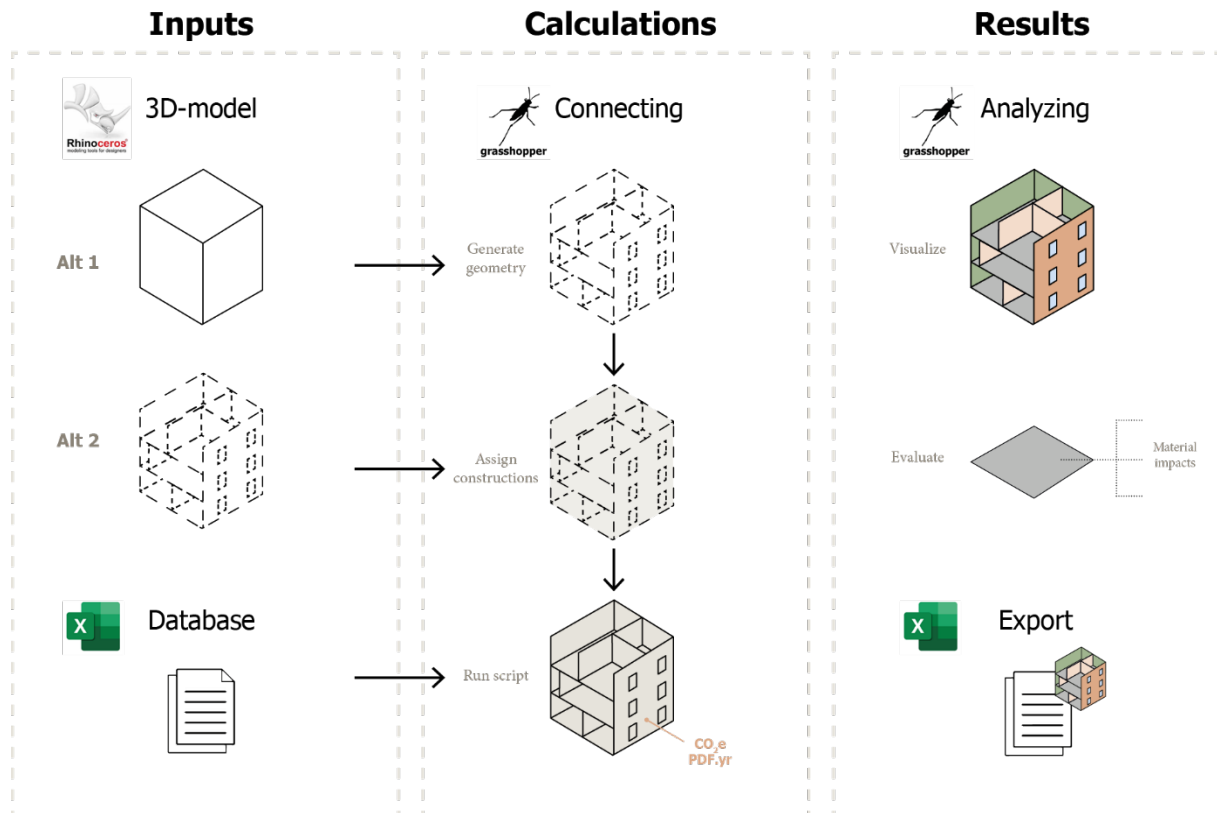


Figure 18. The functional framework of the tool

4.2.1 Geometry inputs

To enhance the flexibility of the tool, geometric inputs for the calculations can either be generated directly within the tool or assigned from a building model in Rhino. Most building components are represented as surfaces, while meter-based components, such as strip foundations, beams, and columns, are assigned as curves. Figure 19 shows an example of a parametric building model generated in the tool, where some geometry are hidden to display other. The amounts of windows, inner walls and core walls are based on expert-derived ratios from the research project LCA Volume by Aarhus University (2026).

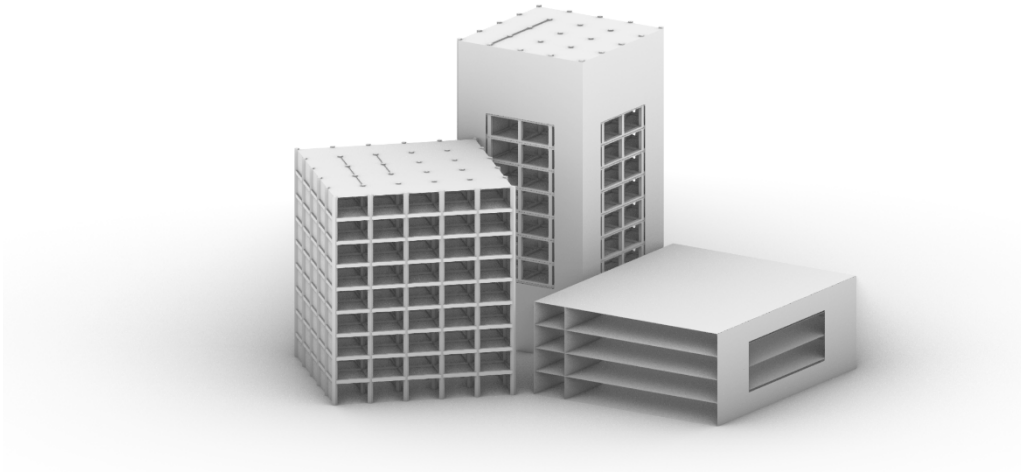


Figure 19. Example of generated geometry based on assigned volumes

4.2.2 Assigning constructions

The database contains a catalogue of construction layers for each building components, including some pre-defined complete options for roofs, windows and doors. The impact data is assigned per m² for all constructions apart from columns, beams and line fundamentals that are assigned per m. User selections inside Grasshopper is made from drop-downs of the available constructions layers forming a complete component (see Figure 20).

SELECT BUILD-UP

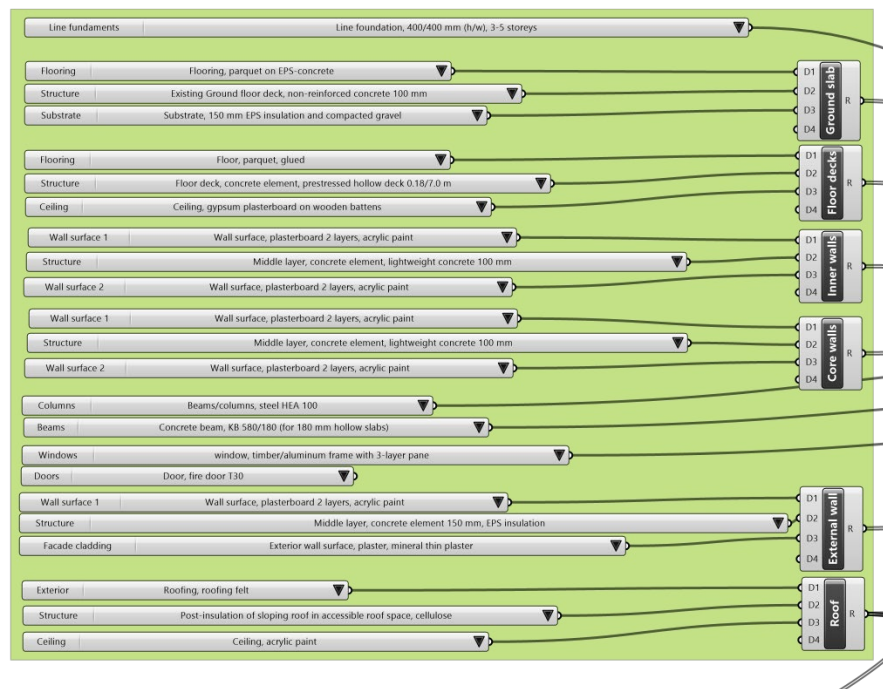


Figure 20. Users build their constructions inside the script

An example of available selections for a construction layer is shown Figure 21, displaying the options for outer surfaces of exterior walls with their corresponding impacts.

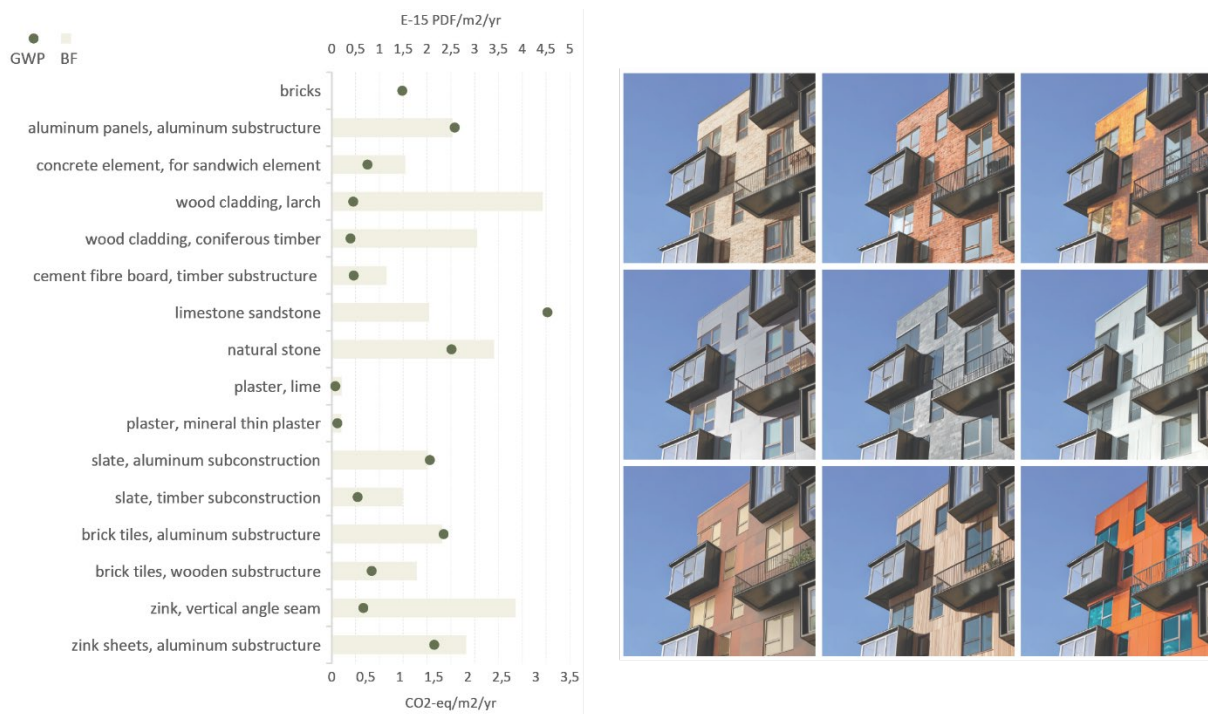


Figure 21. Outer surface layers for exterior walls in the construction library

4.2.3 Estimating impacts

The database Excel file is input to the script together with the geometry for each component and the corresponding selected construction types. Areas are calculated for the surfaces, as well as lengths for the input curves, and multiplied with imported impacts from the database. Calculations are performed per building component and summed to get the total impact for both GWP and BF, with details on the contributions of each driver to the biodiversity impact and the distribution throughout the life cycle. The calculated impacts can be further weighted after location and forestry practice for the different biomaterials in an additional component for sensitivity studies. Currently, the script only allows for the selection of the same country for all biobased materials, or based on the European market. The categories of biobased materials are listed below.

- Cross-laminated timber (CLT)
- Door, inner, wood
- Fibreboard (high-density, HDF, hardboard)
- Fibreboard (medium-density, MDF)
- Fibreboard (low-density, particle board, chipboard)
- Glued laminated timber (glulam)
- Plywood
- Sawnwood (hardwood)
- Sawnwood (softwood)
- Window frame, wood
- Wood wool

The results are displayed per building component and for the whole building, according to Figure 22.

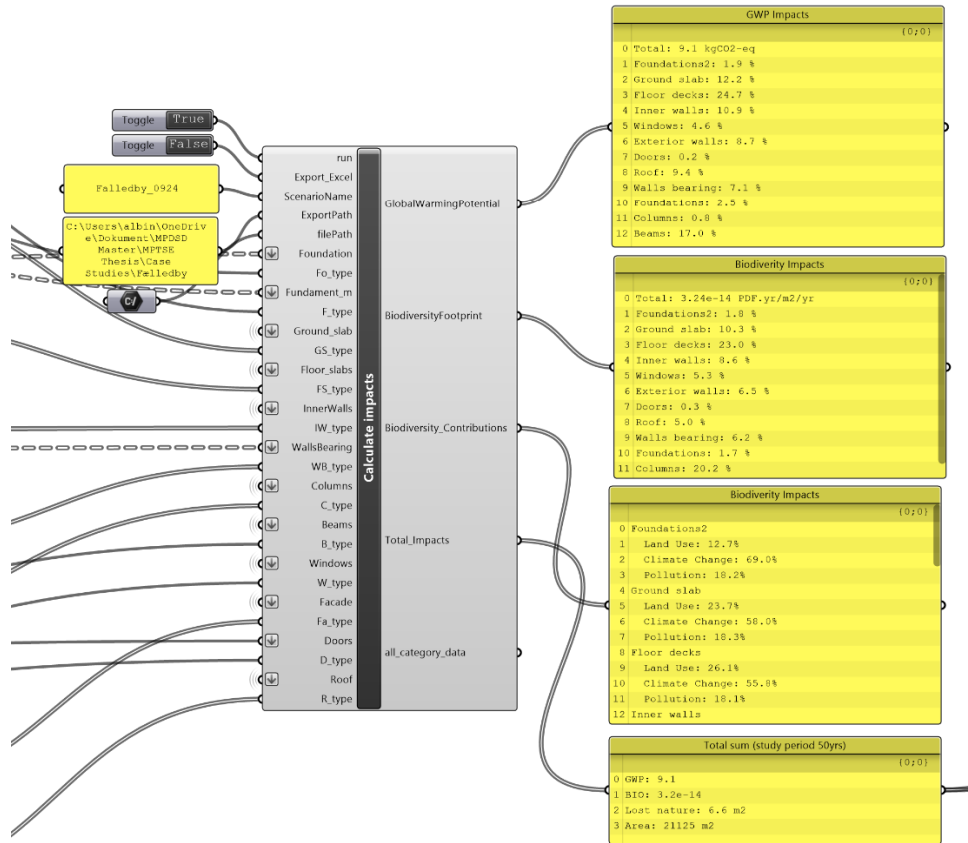


Figure 22. The main calculation component in the script

To study the results more in detail, building components of interest can be further examined in the component as shown in Figure 23. For further analysis, the results can be exported to Excel by assigning a folder path and file name.

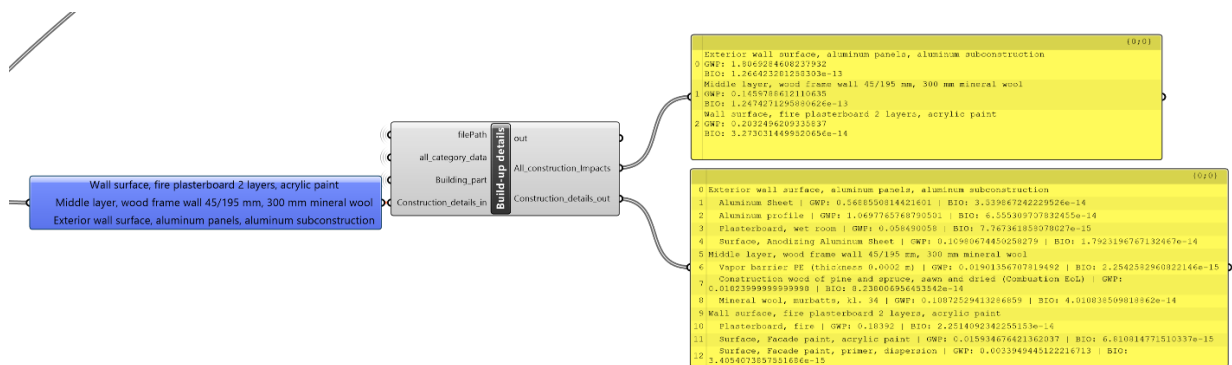


Figure 23. The component for analysing building part impacts more in detail

4.3 Case-studies

The below chapter contains the results of the performed case studies, starting with an exploration of the biodiversity impact assessment results in the first case study. The second case study bridge the detailed results from a complete building LCA with the developed tool for early-design models to validate the tool outputs. The final case study serves as an example of how the tool can be used in the architectural design process.

4.3.1 Case Study 1: Green Hub House

From the biodiversity impact results shown in Figure 24, obtained in the BBV Biotool it is clear that the choice of timber construction is the highest driver of the biodiversity impact. An overview of the total contributions of materials to both GWP and BF is shown in Figure 24. The impacts show that by focusing only on carbon, there is a risk of escalating the biodiversity loss. As a result of timber products specifically having a very low carbon footprint, this can lead to a too high emphasize on timber products, threatening our ecosystems. By only making decisions after GWP, this can have a scaling negative impact on our ecosystems.

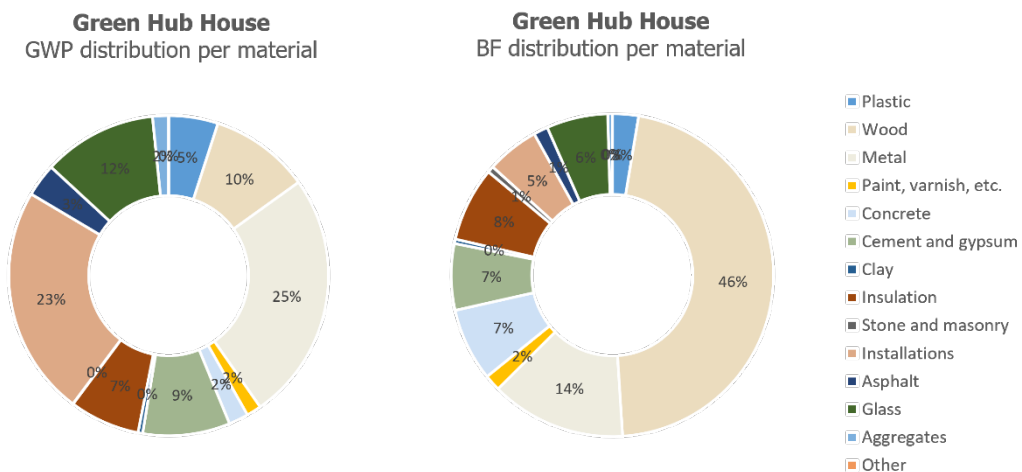


Figure 24. Material distribution of biodiversity and global warming impacts for the Green Hub House

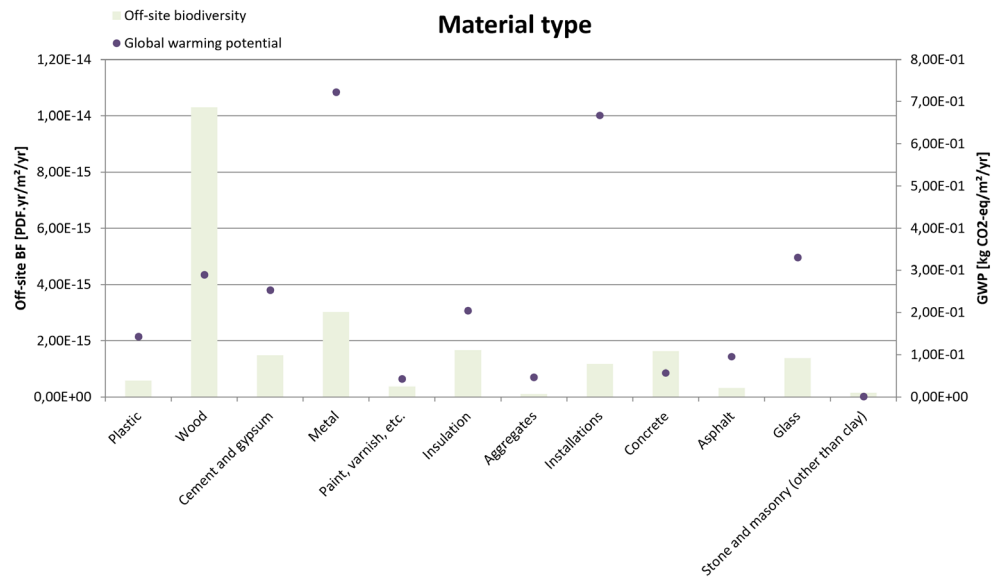


Figure 24. Material contribution to biodiversity and global warming impacts of Green Hub House

Figure 25 shows that the floor decks are the largest contributor to the biodiversity impact by far, while for GWP, windows and doors as well as ventilation contribute as much to the footprint.

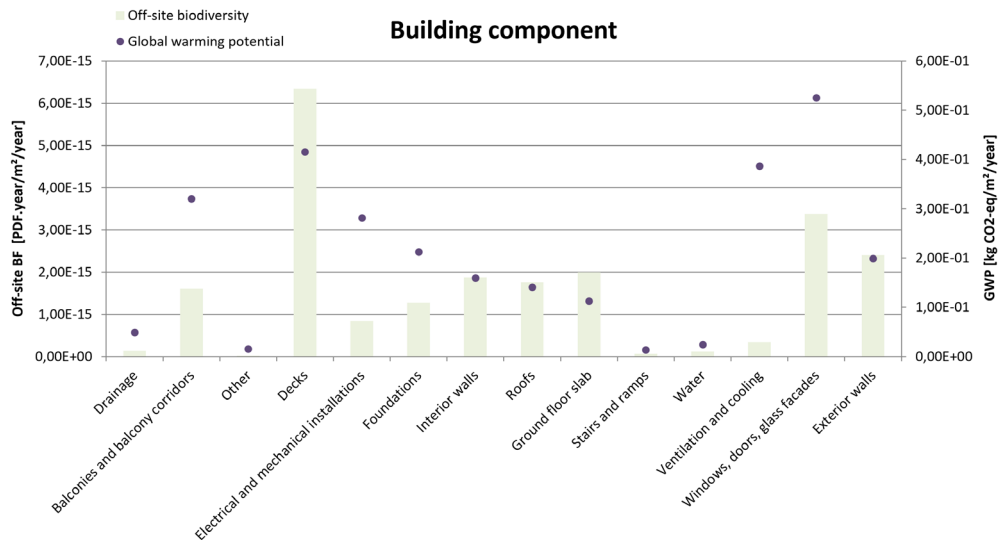


Figure 25. Biodiversity impacts per building component in the Green Hub House

A deeper analysis of the floor deck visualized in Figure 26 shows that the impacts stems from the construction timber and wood flooring.

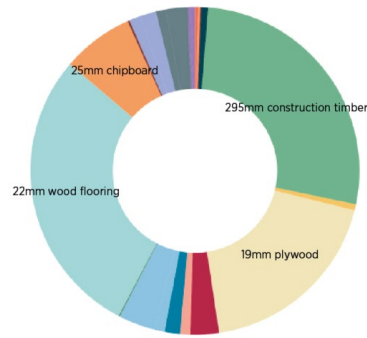


Figure 26. Biodiversity impact contributions for each building material in the floor decks

Further, Figure 27 shows the contribution of drivers to the biodiversity impact displays that land use takes up a large share for the bearing constructions where the timber frames are found. This result also showcases the potential of reducing biodiversity impacts if the land type and forestry management of the biobased materials are taken into consideration

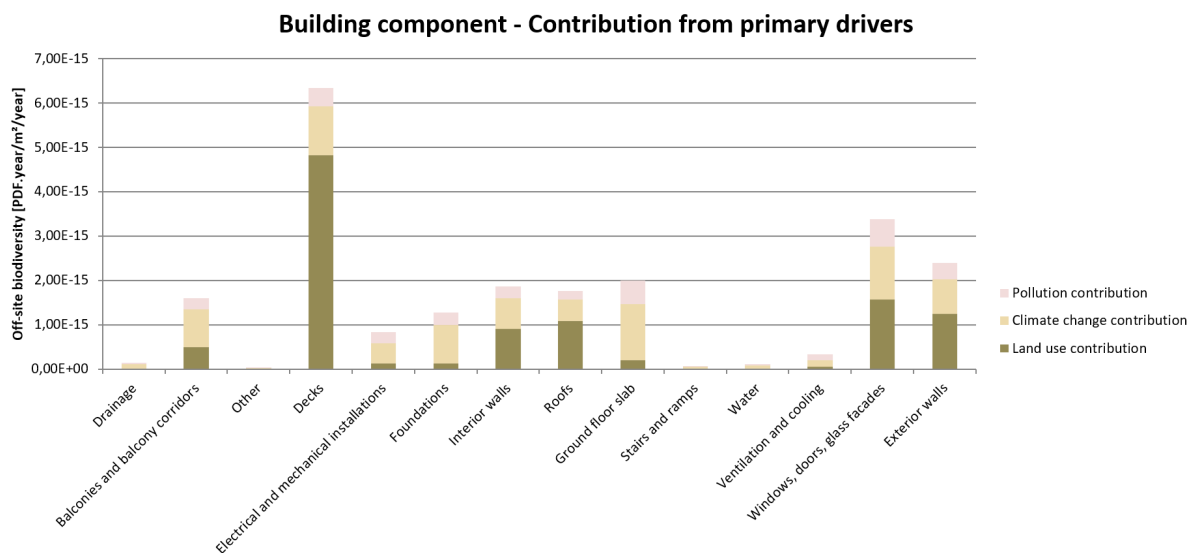


Figure 27. Contribution of biodiversity drivers per building component

To put the overall results into context, a comparison is made in Figure 28 displaying the total footprints of the Green Hub House in relation to the BR18 climate regulations for GWP, and the suggested baseline based on the BBV case library (Upstream Partners *et al.*, 2025). The results show that, despite the timber construction, the project is 41% below the suggested baseline by BBV for biodiversity impacts and simultaneously 57% below the current climate regulations for CO₂e.

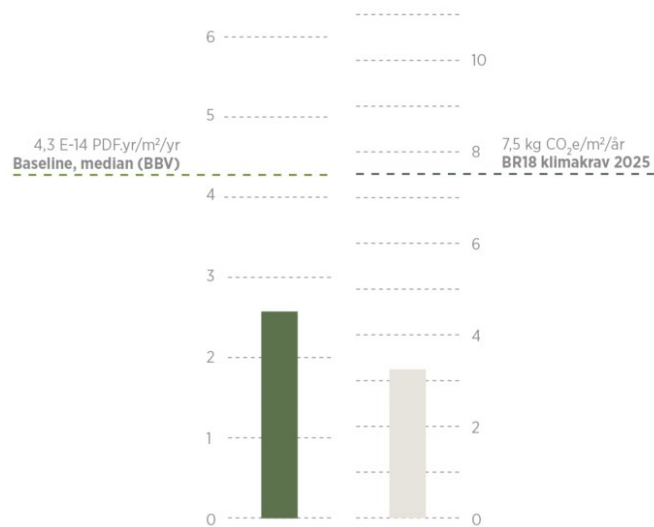


Figure 28. BF and GWP results of the Green Hub House compared to benchmarks

The potential trade-offs between biodiversity and global warming impacts for low-carbon design strategies are further examined in Figure 29. This is done by comparing the timber frame version of the *Green Hub House* with a previously developed hybrid concrete alternative, as well as another residential project, *Ripple Residencies* by Henning Larsen Architects, which is also part of the 4-to-1 Planet project. Results show substantially larger biodiversity impacts for *Ripple Residencies*. The design strategies used in this project to reduce carbon impacts were mainly material reuse and designing for disassembly using CLT modules (*Ripple Residence* | Henning Larsen, no date).

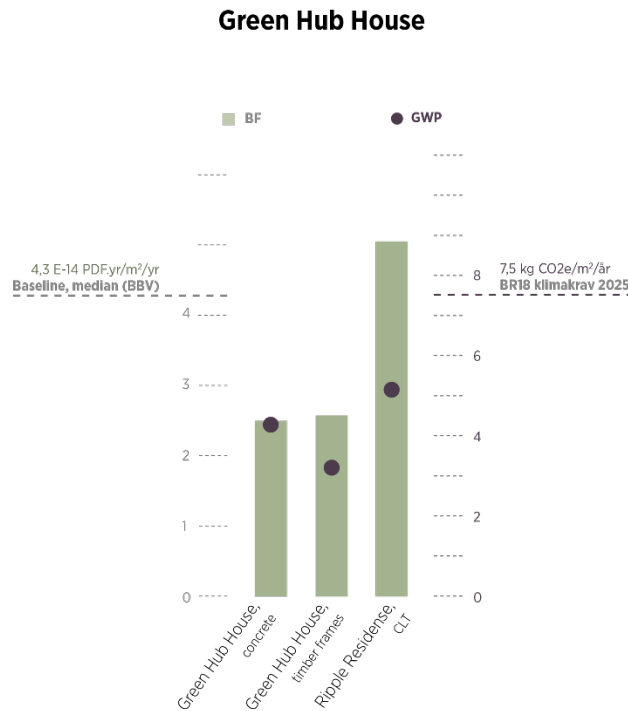


Figure 29. Comparison of GF and GWP impacts between Green Hub House and Ripple Residences

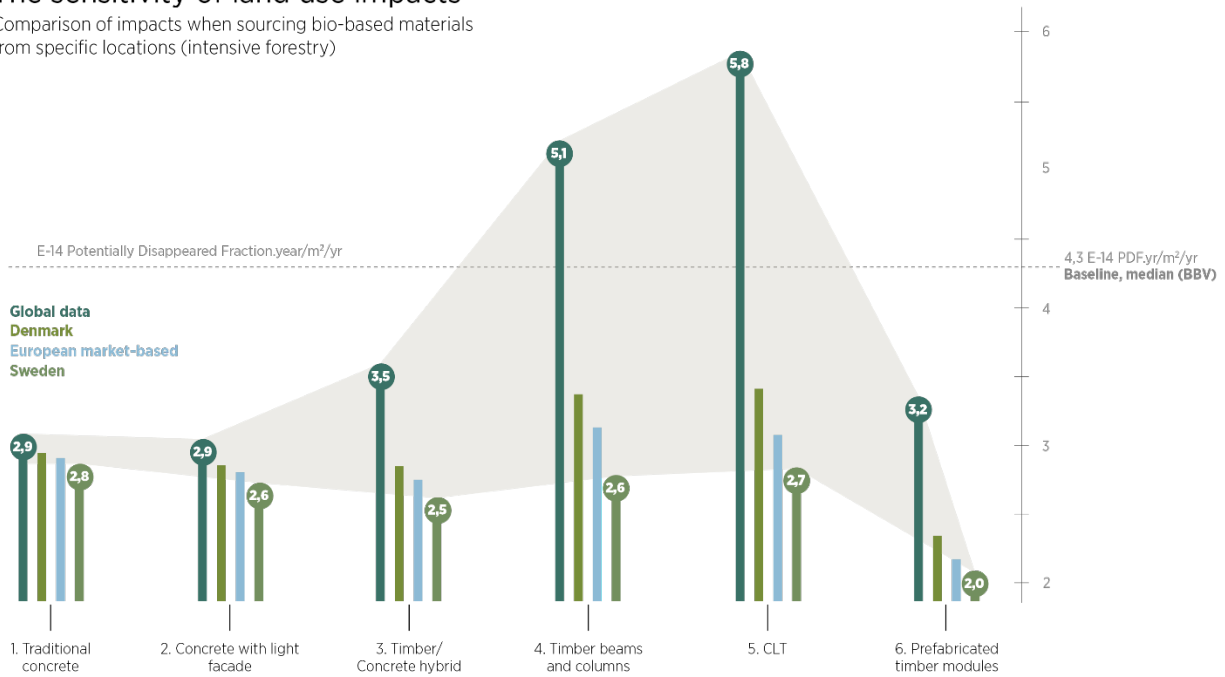
4.3.2 Case Study 2: Balance Boliger

In this case study, biodiversity impacts are investigated as an additional dimension to the *Balance Boliger* project by CF Møller Architects, investigating six generic build-ups of a classic Danish residential building presented in 3.5.2 Balance Boliger.

The total biodiversity impacts were assessed in the BBV Biotoool, and a sensitivity study on country-specific sourcing of biobased materials were made to investigate the impacts from land use driver. The results are shown in Figure 30, displaying that CLT have the highest impact were global average data is used. However, by selective sourcing of bio-based materials, impacts from land use can be reduced to perform better than traditional concrete structures if, for example, Swedish products are used. Adding to that, a reduction of GWP by specific selection of materials with recycled contents, can further reduce impacts from the climate change driver, resulting in a potentially larger improvement. If, on the other hand, the reduction stems from certificates of green origin (GO) for green power supply, biodiversity impacts may be increased.

The sensitivity of land use impacts

Comparison of impacts when sourcing bio-based materials from specific locations (intensive forestry)



Balance Boliger

Off-site Biodiversity Impacts
incl. heat and electricity

Figure 30. Sensitivity study on country-specific sourcing of bio-based materials

The contributing drivers to the impacts are shown in Figure 31.

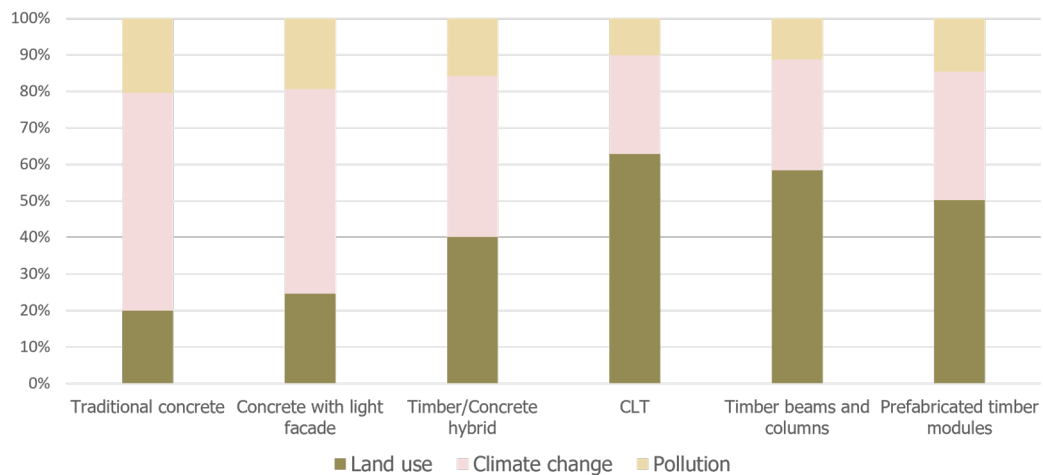


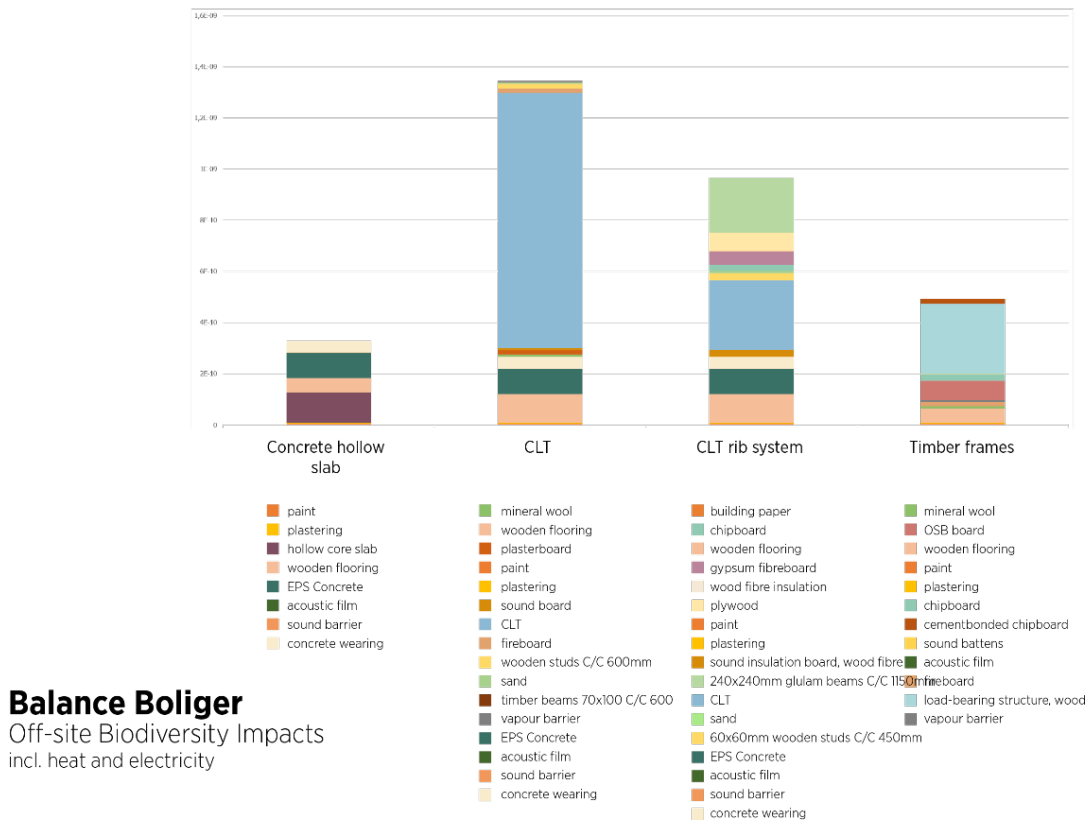
Figure 31. Contribution of drivers to the biodiversity impacts of the analysed building types

The building components contributing most significantly to the overall impacts were floor decks and internal walls, which were also the components showing the greatest variation between the analysed cases. A breakdown of the building material contributions associated with each floor deck system is presented in Figure 32. The hollow-core slab system was used across

all concrete structural solutions analysed in *Balance Boliger*. The results indicate that structural timber is a major contributor to impacts within the wood-based systems, with particularly high impacts associated with the use of CLT.

Floor deck impact distributions

Evaluation of building materials contributions to total impacts of the floor decks in each structural system



Balance Boliger
Off-site Biodiversity Impacts
incl. heat and electricity

Figure 32. Building material contribution to floor deck impacts

To further examine the relationship between BF and GWP, the results based on generic data were overlayed with previously developed GWP results from the *Balance Boliger* project. As illustrated in Figure 33, the hybrid structure and timber module systems show the most balanced performance across the two impact categories, whereas the CLT structure demonstrates the greatest discrepancy between GWP and BF. The study indicates that replacing a conventional concrete structure with a CLT-based solution can reduce the carbon footprint by approximately 30%, while simultaneously increasing the biodiversity footprint by 95% if using global data. However, when applying European market-based data, both biodiversity and global warming impacts for CLT and timber frame structures are considerably more balanced. The lightweight structure with prefabricated timber modules performs well across both impact categories, suggesting that material optimisation strategies represent an effective approach for reducing overall environmental impacts.

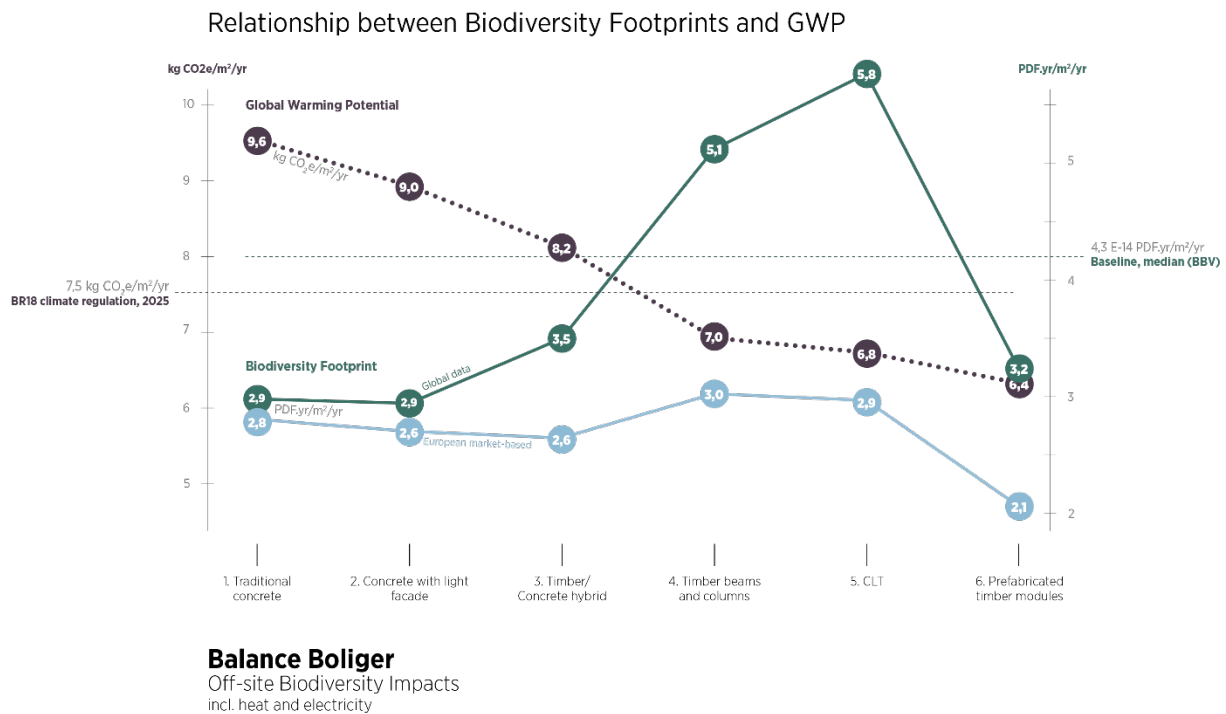


Figure 33. Study of the relationship between biodiversity impacts and carbon footprints.

To verify the applicability of the developed design tool, a volumetric building module was modelled in Rhino. Generic constructions from the developed library were then assigned to the model by selecting the closest matching assemblies for each building type. Figure 34 compares the results obtained from the design tool with those derived from the detailed LCA export based on exact material quantities and construction assemblies. Since the developed tool does not include all building components, a comparison only with the elements represented within the tool framework is also shown. The comparison demonstrates that the generic construction library provides a close approximation of the detailed results, and more accurate modelling of geometries for later conceptual stages will further improve alignment.

Verification of the developed tool

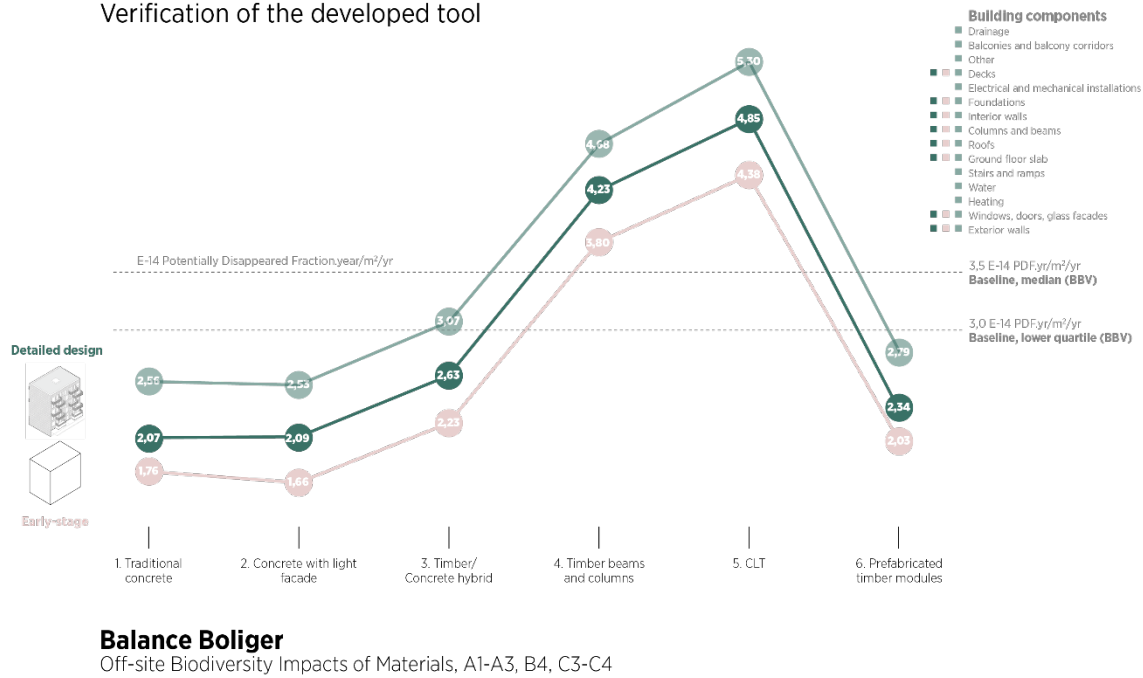


Figure 34. Biodiversity results derived from the early-design tool compared with the final LCA

4.3.3 Case Study 3: Fælledby School

This case study is used to demonstrate how the tool can support design explorations throughout the early conceptual stages. Figure 35 shows a comparison of early-stage design options made with the tool. The selected constructions are constant throughout the study, and the build-up is a column-grid structure with 5mx5m. Figure 36 shows a later stage model derived from floor plan studies, where the impacts are visualized for each building material inside the inner wall constructions.

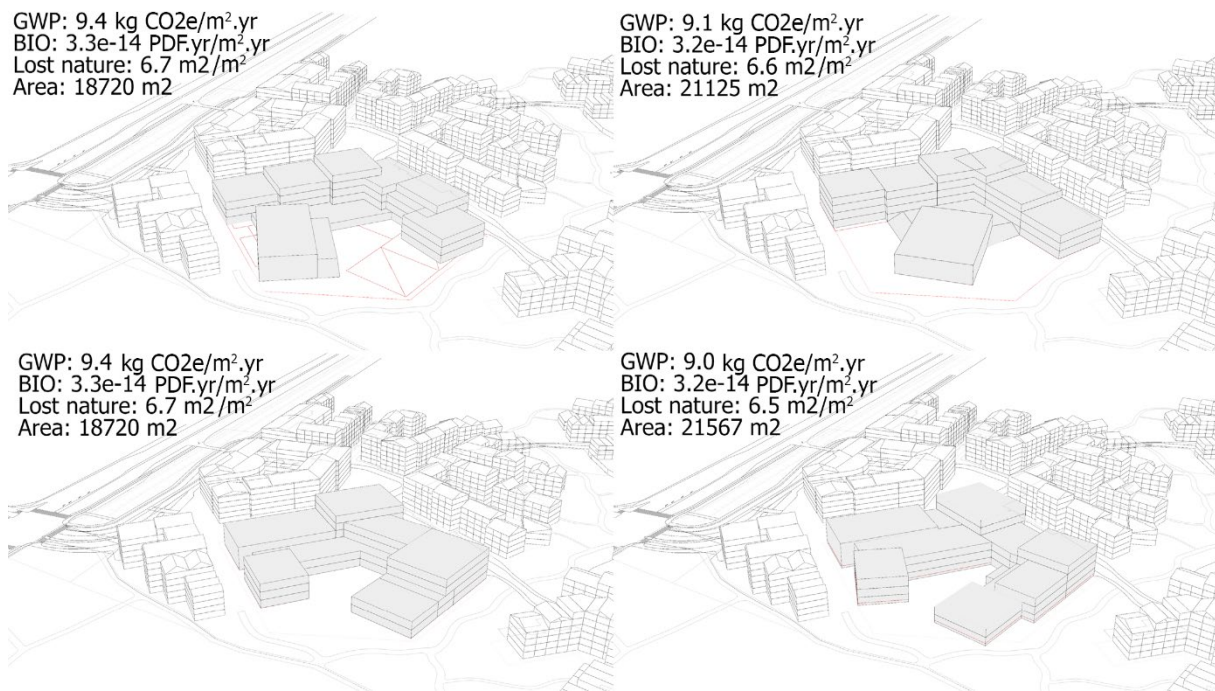


Figure 35. Study of early design options for Fælledby School made with the tool

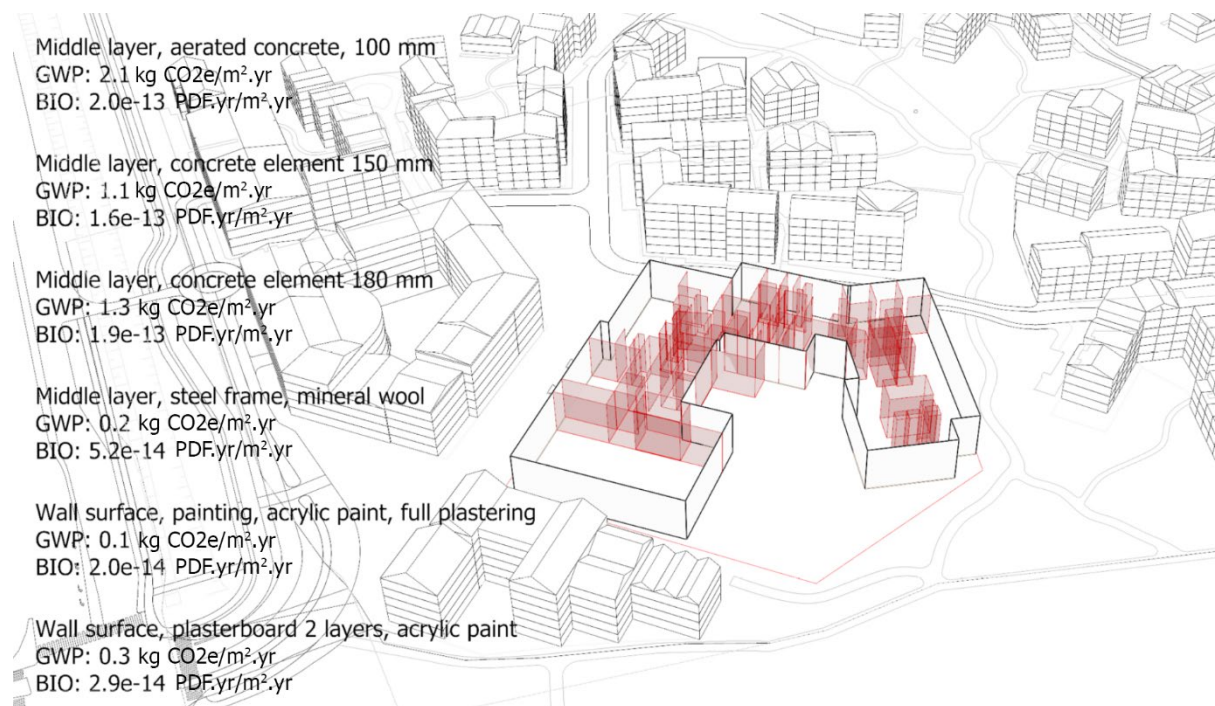


Figure 36. Study on component-level made with the tool, displaying impacts of the inner wall structures

5. Discussion

This chapter presents a discussion of the results and implications of the developed design tool and case studies. It reflects on how biodiversity impacts vary across building systems, and the integration of the assessment in practice. Lastly, a discussion on the potentials and limitations of the tool, including further developments.

5.1 Biodiversity impacts across building systems

This section analyses and discuss the biodiversity impact results derived from the case studies, with a particular focus on their relationship to GWP, sensitivity to material sourcing, and key drivers of impact, followed by implications for design decision-making.

5.1.1 Potential trade-offs between biodiversity impacts and GWP

The results demonstrate that biodiversity footprint impacts vary considerably across building types, structural systems, and material sourcing scenarios, and that these variations do not consistently correspond to global warming impacts. This confirms that biodiversity impacts represent a distinct environmental dimension important to consider. The case studies further reveal that common decarbonization strategies risk having a negative impact on biodiversity when conventional materials are replaced by timber.

Timber-based systems generally perform well in terms of GWP, but their biodiversity performance depends strongly on geographical sourcing, and material quantities. In contrast, concrete structures show more stable biodiversity impact patterns, as they have lower dependence on land-use impacts. The Green Hub House study illustrates this complexity. Although the project achieves a low GWP through extensive timber use, its biodiversity impacts remain comparable to alternative concrete structures when applying generic land-use datasets. Hence, the study demonstrates that timber structures are not inherently associated with high biodiversity impacts. Similar tendencies were identified in *Balance Boliger*, where biodiversity impacts varied substantially between timber construction systems. A timber frame structure reduced biodiversity impacts by approximately 40% compared to CLT, which aligns with findings by (Sigvert *et al.*, 2025). The lower impacts are primarily related to reduced material amounts and lower structural weight. These findings indicate that structural efficiency and material quantity may be as influential for biodiversity impacts as the material category itself.

However, as the findings suggest that most timber structures have high biodiversity impacts, decarbonization strategies relying heavily on bio-based materials may risk overlooking biodiversity consequences. Francart *et al.* (2024) similarly argue that current low-carbon policies may unintentionally increase biodiversity pressures through growing demand for forest-based materials. This tendency is reflected in Figure 37, which shows the DGNB scores for the structural systems in *Balance Boliger*. The results demonstrate that systems with higher shares of timber achieve higher DGNB scores due to lower GWP, while also displaying the highest biodiversity impacts. This raises questions regarding how sustainability performance is currently evaluated within certification frameworks that primarily prioritize carbon reduction.

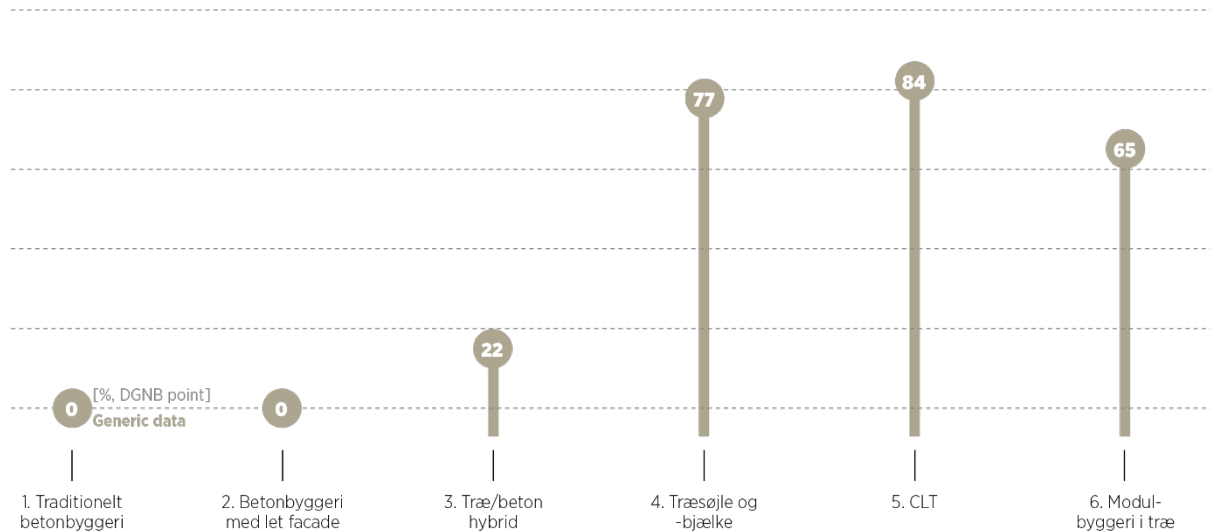


Figure 37. The DGNB scoring of each structural system in Balance Boliger (Adapted from CF Møller Architects)

Likewise, some carbon reduction strategies within material production, such as replacing fossil fuels with bio-based energy sources, may reduce emissions while simultaneously increasing land-use impacts. Strategies focused on reducing material demand and increasing recycled content may therefore provide a more balanced approach across environmental categories. At the same time, the relationship between carbon reduction and biodiversity impacts at building scale remains insufficiently understood, particularly regarding the interactions between land use, renewable energy systems, and bio-based production chains.

5.1.2 Influence of sourcing and land-use assumptions

The results further demonstrate that biodiversity impacts are highly sensitive to geographical sourcing and land-use assumptions. In *Balance Boliger*, sourcing bio-based materials from Sweden reduced impacts from the CLT scenario by approximately 53%, resulting in lower impacts than the traditional concrete alternatives. Findings by Nørrekær Mortensen et al. (2025) similarly indicate that timber sourced from Nordic and Central European forestry can reduce biodiversity impact by up to 70-95% compared to global averages. This highlights how generic datasets may obscure substantial regional differences in forestry practices and ecosystem impacts.

The sourcing study also underlines an important distinction between biodiversity and climate assessments. Whereas carbon emissions contribute to globally distributed atmospheric effects, biodiversity impacts are strongly location-dependent and tied to specific ecosystems and land-use transformations. Consequently, biodiversity impacts cannot be interpreted or compensated

for in the same manner as climate impacts, since ecological losses in one context cannot simply be restored elsewhere without losing ecological specificity.

However, while sourcing strategies significantly influence calculated impacts, it remains unclear whether these reductions reflect improved ecological management in areas with low biodiversity impacts or are primarily a consequence of a lower baseline biodiversity due to previous ecological damage. If the baseline is a comparison with species richness in natural habitats or based on measures from a specific time such as pre-industrial, may therefore also affect what geographical areas that generate a low biodiversity impact. Prioritising material production in areas that already exhibit low biodiversity may risk further ecological degradation, effectively shifting environmental pressure geographically. This raises questions about whether such strategies may lead to a form of land sparing system, where pressure is displaced to intensively managed regions while other ecosystems are effectively left untouched, and whether this in turns represents a sustainable approach in the long term.

Furthermore, the current land-use classes included in LCIA methods are insufficient to provide a fully representative assessment of land-use-related biodiversity impacts. The IW+ method distinguishes six land-use types (cropland, pasture, plantations, managed and natural forests, and urban land), which limits its ability to capture important ecological variation within land systems, such as differences between forest types and specific data for timber species. Bio-based materials such as reed, typically occurring in transitional aquatic–terrestrial zones, also lack a dedicated land-use category and are therefore approximated using existing types. Moreover, ecological parameters such as regeneration time for specific vegetation are not included, which may influence the assessment of ecological damage. This is particularly relevant for comparison between rapidly regenerating materials such as straw, bamboo, or reed with slow-growing timber species, where regrowth can span several decades, as this may affect the biodiversity impacts. In addition, bio-based building materials often utilize agricultural by-products rather than primary cultivation outputs, raising questions regarding the appropriate allocation of biodiversity impacts in these occasions.

5.1.3 Building components and impact drivers

Across the case studies, the largest biodiversity impacts consistently originated from floor decks, followed by walls, windows, and ground floor slabs. Similar trends were identified by Nørrekær Mortensen et al. (2025), indicating that structural systems and load-bearing components dominate biodiversity impacts due to their large material quantities.

The analysis of impact drivers in Green Hub House and *Balance Boliger* further revealed clear differences between structural systems. In concrete-dominated buildings, climate change impacts were the primary contributor to biodiversity loss, whereas land-use impacts dominated in timber-based systems. This corresponds with the BBV case studies, where average impacts of the case study catalogue consisted of 42% land use, 35% climate change, and 23% pollution-related impacts (Upstream Partners et al., 2025). These tendencies are also visible at a global context, where these drivers together stand for around 60 % of biodiversity loss (IPBES 2022).

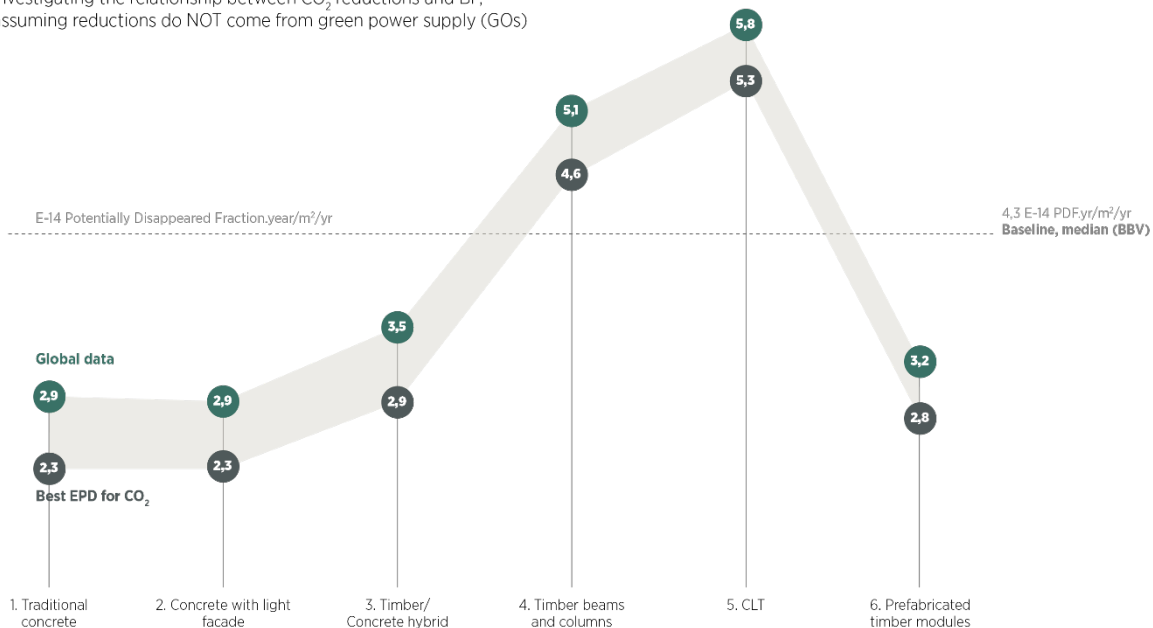
Hence, drivers beyond land-use should not be neglected, and reductions in GWP may also influence biodiversity impacts substantially depending on their underlying mechanisms. Carbon reductions achieved through renewable energy certificates (GOs) may affect

biodiversity impacts negatively. In contrast, reductions based on recycled content or material efficiency may lead to more direct decreases in both climate and biodiversity impacts.

A study conducted on *Balance Boliger* explores this relationship by selecting building products based on EPDs with the lowest GWP and assessing the corresponding changes in biodiversity footprint compared to global values (see Figure 35). However, this scenario assumes that emissions reductions originate from recycled content or similar strategies, and not from GOs, which is often not the case. The analysis therefore serves primarily as an illustrative example, demonstrating that substantial reductions in biodiversity impacts can also be achieved by addressing other drivers.

The sensitivity of climate change impacts

Investigating the relationship between CO₂ reductions and BF, assuming reductions do NOT come from green power supply (GOs)



Balance Boliger

Off-site Biodiversity Impacts
incl. heat and electricity

Figure 35. Study on the potential relationship between carbon reduction and biodiversity impacts

The results therefore indicate that reducing biodiversity impacts cannot be approached through a single strategy. Measures aimed at reducing carbon emissions may shift impacts towards land use and resource pressure, particularly when relying on bio-based materials and fuels. Consequently, biodiversity assessment introduces a broader perspective on environmental trade-offs within building design.

5.1.5 Implications for design decision-making

The findings demonstrate that biodiversity assessment can contribute additional information to decisions on structural build-ups and materials by identifying impact hotspots and performing variant studies. Since BF and GWP do not consistently align, evaluating biodiversity impacts alongside climate impacts can support more balanced environmental assessments and reduce

the risk of single-issue optimization in low-carbon building strategies. The case study results indicate that high biodiversity impacts often stem from aspects such as forestry practice and geographical location. However, the current lack of product-specific data and level of detail in the methodology behind the biodiversity assessment do not yet support decisions to be made on a material level. The findings from the case studies of timber products having in general high impacts can therefore not be seen as a conclusion, as the assessment is too simplified. Therefore, the findings do not imply that timber as a material should be ruled out, but rather that design strategies and material decisions should take forestry practices, land use, and geographical sourcing into account as far as possible. More broadly, the results suggest a need to rethink how sustainability is integrated into building design practice, and how strategies for a sustainably built environment are developed.

5.2 Uncertainties and interpretation of biodiversity impacts

The findings from the case studies indicate that biodiversity impacts are often strongly driven by specific materials and building products within a structural system, especially for timber-based constructions such as the CLT system. This suggests that biodiversity assessment may currently be more relevant at the level of material production and manufacturing in order to reduce impacts, as relatively small changes in forestry practice, sourcing, or product composition can significantly influence results. This sensitivity also highlights the large uncertainties of the impact results, and that more detailed product-level information regarding geographical origin and production of the materials are needed in order to support meaningful discussions and decisions within building projects.

This conclusion is reflected in the recent statement by EPD Denmark that biodiversity impact indicators will not yet be implemented in EPD frameworks due to the large uncertainties related to location specificity and methodological variation (EPD Denmark, 2026). However, this argument can also be questioned. Eegholm et al. (2025) demonstrate that while different LCIA methods vary to some extent in magnitude, variation is mostly related to the drivers behind the impacts, and the overall impact trends remain relatively consistent across methods, with the exception of the more experimental PB-LCIA framework based on planetary boundaries. Similarly, comparisons between background LCI databases such as ecoinvent and BAFU indicate relatively limited variation in total results (ConTech Lab, Sweco and Aaen, 2026). This suggests that, despite uncertainties, biodiversity assessment may still provide meaningful comparative insights when data is more developed and should not necessarily be disregarded on methodological grounds.

Professor in biodiversity, Carsten Rahbek, at the University of Copenhagen further argues that meaningful integration of biodiversity impacts into LCA and EPD frameworks would ideally require site-specific ecological data for the exact forestry areas and land-use systems involved, as biodiversity conditions can vary substantially even within the same country (Rahbek, 2026). However, implementing such detailed field measurements within industrial practice would be highly challenging. Moreover, similarly detailed site-specific data is generally not available for carbon assessments either, as the primary purpose of LCA frameworks is more large-scale comparative evaluation rather than an exact quantification measure. The challenge therefore becomes how biodiversity impacts can be integrated into scalable assessment methods while still maintaining sufficient ecological relevance.

To summarize, findings from the case studies should not be interpreted as demonstrating that timber is inherently a worse material choice than concrete from a biodiversity perspective. Such conclusions would oversimplify the complexity of the assessment and overlook the significant influence of assumptions on sourcing conditions for the materials. Likewise, the study does not provide a basis for determining how BF should be weighted against GWP, nor how trade-offs between the two should be prioritised within sustainability targets, as of the current uncertainties.

Additionally, no common benchmark exists for relative comparison of the two indicators, and is potentially not valid to introduce, making it difficult to conclude on how to work with the two measures together. The planetary boundary frameworks indicate that biodiversity loss has exceeded ecological limits to a greater extent than climate change, while diverse ecosystems also play a critical role in climate regulation and carbon sequestration (IPBES, 2019). This highlights the importance of biodiversity to also function as a regenerative strategy essential for further long-term mitigation of climate change, whereas carbon reduction may provide more of a direct effect in reducing environmental pressure.

5.3 Potentials and limitations of the developed tool

The developed interface of the design tool responds to the industry's need for more accessible tools by reducing complexity compared to traditional Excel-based LCA tools such as the BBV Biotool, enabling impact evaluation without requiring a full project-level LCA setup. The tool update results interactively and have a reduced amount of user selections. At the same time, this simplification introduces limitations, such as geometric assumptions, dependencies on predefined construction assemblies and require a basic understanding of structural systems. The parametric framework although demonstrates the potential for linking biodiversity assessment data with architectural geometry in a flexible and relatively accessible workflow. The tool enables rapid comparison of design alternatives and visualization of biodiversity hotspots across building elements and assemblies. The results generally align with more detailed LCA-based assessments, although they tend to be lower as the tool excludes several lifecycle stages and focuses primarily on embodied material impacts.

Operational energy is not included, even though it can represent a significant share of biodiversity impacts. Previous studies by Francart *et al.* (2024) report contributions of 64% for an office building and 39% for housing. However, results from the Green Hub House and *Balance Boliger* indicate lower shares of around 10-20% for heat and electricity contributions. Materials contributed with around 70-80% of total impacts, which aligns with the average of 60% in the BBV project (Upstream Partners *et al.*, 2025). This suggests that tool-based results may underestimate total life cycle impacts by roughly 20–30%. On-site biodiversity effects are also excluded, despite their potential variability of -3.6 to 1,9 E14 PDF.yr/m²/yr according to the case studies (Upstream Partners *et al.*, 2025).

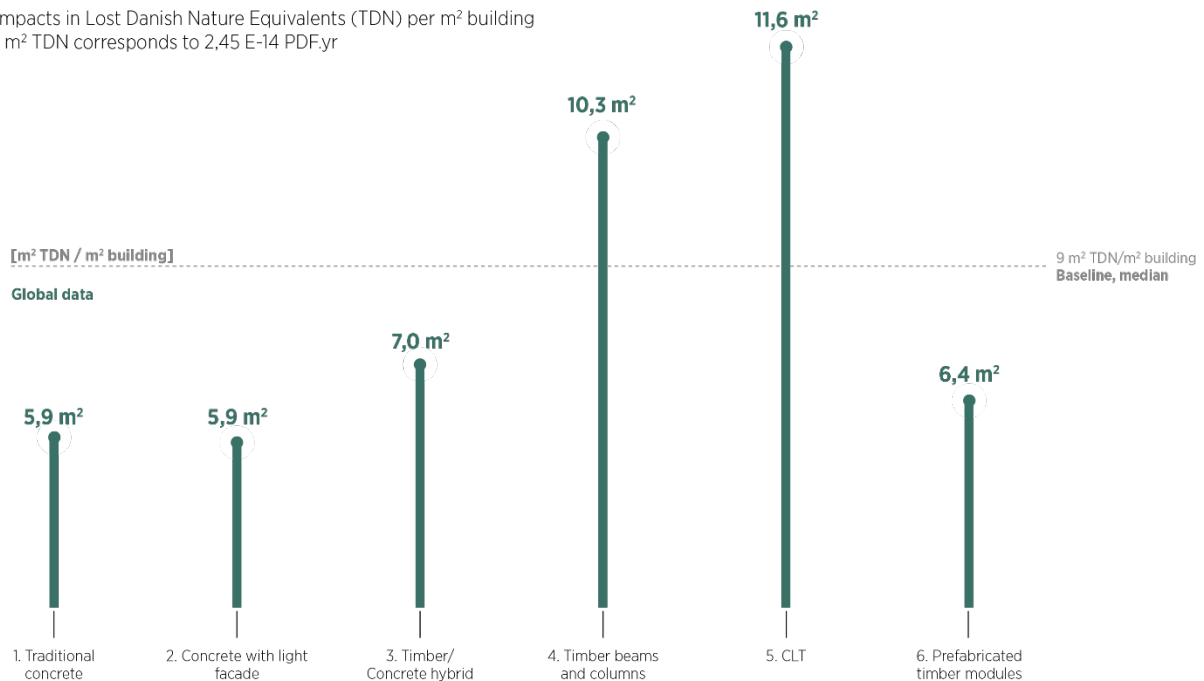
The analysis of the Fælledby school demonstrates how the tool can support iterative exploration of design alternatives with different levels of detail in the assessment. However, the study reveals that the biodiversity impact is not necessarily as sensitive as GWP to geometric variability, assuming the same constructions are assigned. This can be influenced by the aggregation of materials in the BBV Biotool calculations, giving many building products more similar impacts compared to the imported GWP results for each products. Applying the tool in practice also raised questions regarding the appropriate level of detail for biodiversity

assessment within architectural design processes. It can be questioned whether biodiversity impacts can be meaningfully addressed at the building level, or whether effective mitigation instead needs to begin further upstream in the supply chain before any actionable insights can be achieved at the building scale. In this sense, the findings suggest that the focus of the developed tool should be reconsidered and shifted toward more detailed component-level analysis, where variations in materials and construction assemblies can be more directly investigated. Such a focus would better support understanding of biodiversity impacts and could facilitate more meaningful dialogue between designers, engineers, and material producers.

Another challenge lies in the interpretation and communication of results, as the unit is difficult to grasp at building scale, having a factor of E-14. Alternative benchmarks such as the Lost Danish Nature (TDN) metric (Upstream Partners *et al.*, 2025), which translates impacts into equivalent areas of Danish nature, may improve communicability and practical understanding of the results. The impacts from *Balance Boliger* are converted into m² TDN/m² building in Figure 387, showing that the CLT structure corresponds to a nature loss of 11,800m², considering the floor area, which is almost the size of two football fields.

Estimated loss of Danish nature

Impacts in Lost Danish Nature Equivalents (TDN) per m² building
1 m² TDN corresponds to 2,45 E-14 PDF.yr



Balance Boliger

Off-site Biodiversity Impacts
incl. heat and electricity

Figure 38. Biodiversity impacts of Balance Boliger (m² Lost Danish Nature per m² building)

Economic equivalents based on restoration costs may serve a similar function, but should not be interpreted as implying that economic compensation for biodiversity loss is possible. As an example, the Danish Nature Fond have put the price of 1m² Danish nature to 12dkk. This would imply that the CLT structure in *Balance Boliger* corresponds to approximately 140,000dkk in estimated restoration costs, based on the floor area of 1,020m².

To conclude, despite the addressed limitations the tool demonstrates how biodiversity assessment can be operationalized in building design workflows. Its structure allows for extension of the database to include additional construction types, although calculation still depends on building LCA software and the BBV Biotool or similar. Future development should focus on improving automation of calculations, expanding databases with more detailed product-level information, and integrating updated LCIA methods. However, the largest limitation remains the lack of high-resolution and location-specific biodiversity data for materials and production processes. Strengthening this data foundation will be essential for improving robustness and enabling broader implementation of biodiversity indicators within building assessment frameworks and EPD systems. In this context, bottom-up developments from researchers and practitioners may help accelerate updates and encourage integration of biodiversity indicators into building LCA practice.

6. Conclusion

The relationship between biodiversity impacts and global warming potential demonstrates that environmental consequences cannot be fully understood through climate assessment alone. The case studies show that buildings achieving low carbon footprints may instead generate high off-site biodiversity impacts, resulting in burden-shifting rather than mitigation. Replacing conventional building materials with bio-based alternatives as a decarbonisation strategy proves to introduce important trade-offs that must be carefully considered. While some reductions in CO₂ emissions can be achieved, these may be accompanied by substantial and irreversible loss of species if material sourcing and production systems are not considered. This highlights the importance of including geographical origin and supply-chain conditions in material evaluations, particularly for timber-based products where impacts are strongly influenced by land-use change and forestry practices.

At the same time, the results demonstrate that biodiversity impacts vary considerably within wood-based construction systems. This indicates that timber systems are not inherently associated with high impacts, nor is it automatically a sustainable alternative in all cases. CLT structures generally exhibit higher impacts due to material intensity, whereas timber frame systems and prefabricated box-modules perform more favourable, in some cases achieving lower BF than conventional concrete alternatives. These differences underline that design decisions related to structural systems and material quantities play a decisive role in determining overall environmental performance. At the component level, load-bearing elements such as floor decks and walls consistently dominate total impacts, highlighting them as key priorities for design optimisation and mitigation strategies.

To support the investigation of such relationships in practice, the developed tool proposes an approach for integrating biodiversity assessment into architectural design workflows. Through relatively simple and iterative analyses, it enables comparison of design alternatives and identification of project-specific impact hotspots, addressing a clear industry need for more accessible tools that can support environmental evaluation during the design process. At the same time, the results indicate that biodiversity impacts largely originate far upstream in the supply chain, suggesting that optimisation at material and product level may be a better starting point for implementing the assessment than at building scale. In this regard, the tool may be more valuable for exploratory component-level studies that support increased understanding of biodiversity impacts and foster dialogue between designers, engineers, and material producers.

Despite methodological uncertainties and limitations in available data, the framework demonstrates the relevance of biodiversity assessment as a complementary measure for informing discussions on materials, structural systems, and environmental trade-offs in building design.

In conclusion, the thesis suggests that biodiversity assessment is not yet sufficiently robust to function as a deterministic decision-making tool. However, the study clearly demonstrates that the origin and production conditions of building materials are among the most defining factors influencing biodiversity impacts, and aspects that will need to become increasingly integrated into design evaluations and decision-making in the industry. In this context, the developed tool holds value as an exploratory design instrument capable of broadening environmental thinking beyond carbon alone. Continued development of location-specific datasets, product-level information, and more standardised assessment methods will be essential to improve reliability and enable more widespread and meaningful application in practice. Until then, decarbonisation strategies in building design must be more carefully evaluated to reduce the risk of burden-shifting between environmental impact categories. In this regard, prioritising recycled materials and prolonging the lifespan of existing buildings emerge as important sustainability strategies for reducing both climate and biodiversity impacts within the built environment.

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Appendix I – Excel database

This appendix contains the full dataset and calculations used for the environmental impact assessment. The file is embedded for reference and reproducibility.



Appendix II – Biodiversity data

This appendix contains the biodiversity data embedded in the developed script and used in the biodiversity impact assessment calculations.

Product	GLO	GER	DEN	EST	FIN	LAT	NOR	POL	SWE	EU Market-based
Cross laminated timber, CLT	100%	22%	26%	5%	4%	5%	11%	11%	5%	13%
Door, inner, wood	100%	40%	45%	27%	26%	27%	31%	32%	27%	74%
Fibreboard (high-density, HDF, hardboard)	100%	23%	26%	11%	10%	11%	15%	15%	11%	14%
Fibreboard (medium-density, MDF)	100%	24%	27%	13%	11%	13%	16%	17%	13%	15%
Fibreboard (low-density, particle board, chipboard)	100%	22%	25%	9%	8%	9%	13%	14%	9%	12%
Glued laminated timber (glulam)	100%	30%	46%	7%	5%	7%	15%	16%	8%	38%
Plywood	100%	22%	26%	6%	4%	6%	11%	11%	5%	22%
Sawn wood (hardwood)	100%	22%	26%	5%	3%	5%	11%	11%	5%	21%
Sawn wood (softwood)	100%	22%	26%	5%	3%	5%	11%	11%	5%	12%
Window frame, wood	100%	28%	32%	13%	11%	13%	18%	18%	13%	77%
Wood wool	100%	22%	26%	5%	3%	5%	11%	11%	5%	9%

Table 1. Regionalization factors for country-specific land-use impacts, with intensive forestry



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