Shifting to Biobased Building Materials in Animal Housing

Hundaol Dega Gurmessa

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

Lund University

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

Master Program in Energy-efficient and Environmental Building Design

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

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

Examiner: Ulla Janson (Building Services)

Supervisors: Marie-Claude Dubois (Energy and Building Design), Gyorgy Ängelkott Bocz (SLU)

Keywords: Operational energy, Embodied energy, Operational carbon, Embodied carbon, agriculture buildings, animal housing, poultry

Publication year: 2026

Contents

Abbreviations

ADP	Abiotic Depletion Potential
AIA	American Institute of Architects
AP	Acidification Potential
BIM	Building Information Model
CCA	Copper Chromium Arsenic
CFC	Chlorofluorocarbon
CLT	Cross Laminated Timber
DLT	Dowel Laminated Timber
DTU	Technical University of Denmark
EN	European Standard
EP	Eutrophication Potential
EPD	Environmental Product Declaration
EPS	Expanded Polystyrene
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FRP	Fiber Reinforced Polymer
GHG	Green House Gas
GIFA	Gross Internal Floor Area
GLT	Glue Laminated Timber
GWP	Global Warming Potential
HFA	Heated Floor Area
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LVL	Laminated Veneer Lumber

LULUC	Land Use and Land Use Change
NLT	Nail Laminated Timber
NVA	National Veterinary Institute
ODP	Ozone Depletion Potential
OSB	Oriented Strand Board
PCSP	Precast Concrete Sandwich Panels
PIR	Polyisocyanurate
PSL	Parallel Strand Board
PMF	Particulate Matter Formation
POCP	Photochemical Oxidant Creation Potential
REACH	Registration Evaluation Authorization and Restriction of Chemicals
SGBC	Swedish Green Building Council
TBTO	Tributyltin tin oxide
TETP	Terrestrial Eco-Toxicity Potential
UV	Ultraviolet
XPS	Extruded Polystyrene

Acknowledgements

I would like to thank God for giving me this opportunity, for the health and strength to overcome challenges, and for always being on my side. I am deeply grateful to my parents, Mr. Dega Gurmessa and Mrs. Meseret Alemayehu, for their support throughout my studies, as well as to my brother, Yared Dega. A special thanks goes to my beloved sister, Ayantu Dega Gurmessa, whose generosity in covering my tuition fees and living expenses in Sweden made this journey possible. Without her unwavering support, this study would not have been achievable.

Furthermore, I would like to thank all the EEBD teachers who have guided me throughout my studies and helped me deepen my understanding of the subject. I am especially grateful to my supervisor, Professor Marie-Claude Dubois, for her support, guidance, and valuable advice, which I will carry with me beyond this master's thesis. I also express my gratitude to my supervisor from SLU (Swedish University of Agricultural Sciences) György Ängelkott Bocz, for his support, encouragement, and for organizing the site visit to the poultry building under construction in Borby, Sweden. He also facilitated access to the architectural drawings and documents of this project. My thanks also go to Marlab AB for their kind cooperation in allowing the site to visit and provide the necessary documents. I am particularly grateful to Marcus, who took the time to personally explain the construction details on-site, which was highly valuable for the completion of this thesis.

I also thank my examiner Ulla Janson for taking her time to review my thesis and for providing valuable feedback.

Lastly, I thank my classmates for their friendship, support, and the many inspiring discussions we shared throughout this journey. I also express my gratitude to the wonderful people I met in Sweden outside of my studies, Andreas and Deborah Hansen, Charles and Sacha Owusu Ansah whose kindness, friendship and support made my time in Sweden truly memorable.

Abstract

The building sector is the largest contributor to greenhouse gas (GHG) emissions, primarily due to two factors: the embodied energy of construction materials and the operational energy consumed over a building's lifespan. Given this substantial environmental impact, sustainability and climate resilience have become critical priorities in global policy frameworks. Addressing this challenge requires urgent, strategic action, beginning with the informed selection of building materials during the design and construction stages. A key method for supporting such decisions is the use of life cycle assessment (LCA), a method which enables a comprehensive evaluation of a material's environmental impact throughout its entire life cycle.

This thesis focuses on an agricultural building located in Borby, Sweden. The facility is designed as a poultry building to accommodate egg-laying hens. Construction of the building is currently ongoing, and the study is based on the construction drawings obtained from the project. A comparative analysis was performed between two cases: the first represents the ongoing construction, which uses conventional concrete and steel, whereas the second substitutes these materials with biobased alternatives. An LCA is carried out for both options to identify the stages with the highest carbon impact.

The LCA is conducted using Autodesk Revit to extract material quantities, which are then mapped to environmental product declarations (EPDs) in the One Click LCA database. To ensure adequate thermal performance when substituting conventional building materials with biobased building materials, the U-values were calculated based on current Swedish practice.

The comparative LCA between conventional and biobased construction shows that the Global Warming Potential (GWP-total) is reduced by 367 kg CO_2-eq/m^2 of gross internal floor area (GIFA), while the GWP-fossil was reduced by 191 kg CO_2-eq/m^2 in the biobased construction. This reduction indicates lower GHG emissions. In terms of GWP-biogenic, biobased construction exhibits a carbon sequestration potential of 176 kg CO_2-eq/m^2 compared to conventional construction, which offsets a portion of the embodied carbon. Notably, the use of wood purlins in conventional construction contributes to a lower GWP-total.

1 Introduction

1.1 Background and Problem Description

The energy use in a building can be categorized into two areas, namely the embodied energy related to construction and the operational energy use. The embodied energy encompasses the energy used to extract, manufacture, transport, install, dismantle and dispose of the materials whereas the latter refers to the energy used for heating, cooling, ventilation, lighting and equipment during the building's lifetime (Zabalza Bribián et al., 2011). Ramesh et al. (2010) carried out a review of 73 cases across 13 countries, and their finding indicates that embodied energy of buildings accounts for approximately 10-20% of total energy use. In contrast 80-90% of the energy is used during the building's operational phase.

The building sector accounts for approximately 24% of all raw materials extracted globally, contributing significantly to the depletion of the planet's resource base (Zabalza Bribián et al., 2011). This extraction and processing of materials also result in higher CO_2 emissions, which are directly linked to the embodied energy of buildings (Zabalza Bribián et al., 2011). Steel and reinforced concrete are energy-intensive materials associated with high greenhouse gas emissions (Machado et al., 2025). These materials commonly used in conventional construction methods for agricultural buildings in Sweden.

According to the Swedish National Board of Housing, Building and Planning (Boverket, 2022), agricultural buildings belong to one of the categories that are exempt from climate declaration requirement. A climate declaration is based on calculating the equivalent GHG emissions generated during material extraction, production, installation, and transportation. Furthermore, the choice of calculation tool is left for the one preparing the information. Zabalza Bribián et al., (2011) emphasized that LCA is a valuable method for guiding decisions that minimize carbon emissions. In this thesis, the LCA method is applied using One Click LCA as a primary LCA calculation tool.

Balasbaneh and Sher (2024) carried out systematic literature review conducted across different countries which confirm that wooden-framed buildings generally consume less energy and generate lower CO_2 emissions over their life cycle compared to those built with steel or concrete. For example, the embodied energy of a steel-framed structure is 1.61 times higher than a concrete structure, which itself is 1.27 times higher than a timber-based equivalent. Although producing steel elements use 25% less energy per square meter than concrete, buildings made with steel ultimately exhibited greater primary energy use. This outcome was attributed to steel's inferior thermal insulation properties, which resulted in higher energy demand during the operation phase of the building (Zabalza Bribián et al., 2011).

Additionally, Piccardo and Gustavsson (2021), conducted an LCA of building retrofit with three scenarios which are concrete, timber and modular construction. They found that using wood-based materials could reduce non-operational embodied energy by 7–19% compared to concrete, depending on the scenario. Zabalza Bribián et al. (2011) also discussed mitigation strategies: although concrete is associated with significant CO_2 emissions, its environmental impact can be reduced by repurposing it as filler material, thereby extending its usability and offsetting emissions linked to virgin resource extraction.

In previous studies, comparative LCAs using different load bearing construction materials have been carried out to compare the GWP of residential and office buildings by substituting concrete and steel with biobased materials. However, in previous research, little attention has been given to animal housing. Historically, poultry houses were constructed using timber structures and relied primarily on natural ventilation. In contrast, contemporary conventional poultry housing is typically designed as a steel portal-frame structure with insulated façade panels and an uninsulated concrete floor, with mechanically driven ventilation systems, which results in high operational energy use (Campbell et al., 2023).

The exemption of animal housing from the legislative climate declarations despite the use of traditional materials with high GWP, combined with limited research regarding animal housing, motivates this thesis. The thesis carries out a comparative LCA of animal housing comparing two cases; conventional construction which uses concrete, steel and extruded polystyrene (XPS) insulation, and an alternative construction using biobased building materials. The study aims to compare the embodied carbon within the materials used. The building under study is currently under construction in Borby, Sweden.

1.2 Aim

The aim of this study is to contribute knowledge regarding the embodied carbon impact that is overlooked in agricultural building facilities.

1.3 Objective

The objectives of the thesis are to:

- gather construction information about poultry construction;
- estimate the embodied carbon impact of conventional construction and compare this impact with biobased alternatives;
- investigate which biobased solutions are available in the poultry sector;
- identify key life cycle stages that contribute to the highest content in this construction;
- suggest a better approach to decision making to choose materials that mitigate carbon impact in the construction sector;
- demonstrate how using biobased building materials can offset carbon emissions, as materials such as timber can store carbon and generate lower emissions during production compared to steel, concrete, and many insulation materials.

1.4 Scope and limitations

LCA is an iterative process encompassing four stages; the goal and scope definition, inventory analysis, impact assessment and interpretation. The goal of this study is to compare conventional construction materials with biobased alternatives and identify key areas of improvement. The scope of this study focuses on the embodied carbon product stage (A1-A3), as well as construction process stages (A4-A5) and potential of recycling (C stages) and reuse (D stages).

This study does not cover the structural integrity of substituting steel with timber and as such, it is limited in its scope. Literature and other sources were used to approximate the size and structural stability of the design, including considerations of volume and scale. However, these calculations have not been reviewed or verified by a structural engineer. Furthermore, the use stage (B-stages) of the building in each case is not covered as the focus of the study is the embodied carbon and not operational carbon.

2 Theoretical Framework

This theoretical framework discusses the main phases and stages of LCA. Furthermore, it examines the key standards and environmental impact categories used to evaluate the performance of building materials. It also highlights the materials analyzed in this study, including concrete, steel, insulation, and timber products.

2.1 Life Cycle Assessment (LCA)

In developing a certain product, functionality, aesthetics, costs, etc., need to be considered. Earlier typical environmental considerations focused on the emissions of the manufacturing process and did not address distribution, use, and disposal. A life cycle assessment (LCA) considers the whole life cycle of a product. LCA quantitatively evaluates the environmental impact of a product across all stages of its lifecycle. (Lee & Inaba, 2004)

LCA is most often performed based on standards. The foundational standards are outlined by the International Organization for Standardization (ISO). Furthermore, there are also European Standards (EN), which are used in all industries and are subject to building LCA and more. In addition to these foundational standards, construction work-specific standards and environmental product declarations (EPD) standards may apply (One Click LCA Academy, n.d.-c).

Foundational standards

- ISO 14040 LCA: Principles and framework
- ISO 14044 LCA: Requirements and guidelines

Construction work-specific standards

- ISO 21929-1- Sustainability in building construction – Sustainability indicators
- ISO 21931-1- Sustainability in buildings and civil engineering works- Framework for methods of assessment of the environmental, social and economic performance of construction works as a basis for sustainability assessment
- EN 15643 Framework for assessment of buildings and civil engineering works
- EN 15978 Assessment of environmental performance of buildings- Calculation method

EPD Standards

- ISO 14025 Environmental labels and declarations- Type III environmental declarations- Principles and procedures.
- ISO 21930 Sustainability in buildings and civil engineering works- Core rules for environmental product declarations of construction products and services.
- EN 15804 Core rules for the product category of construction products

According to SS-EN ISO 14040:2006, the four phases of LCA are outlined as follows:

- Goal and Scope definition: The goal defines why it is important to carry out the LCA study, and the scope is where the functional unit, system boundary, data category, assumptions and limitations are clearly defined.
- Life Cycle Inventory (LCI): This phase is data collection and calculation on different inputs and outputs of a product. The inputs can be energy, water needs, etc., whereas the outputs can be discharged to the environment.

- Life Cycle Impact Assessment (LCIA): Based on the LCI, the potential impacts of a product are selected. After collecting data emissions from the product that has environmental impact, the impacts are sorted into specific categories and given values using standard units. This phase can also include optional steps like normalization and weighting.
- Interpretation: This phase involves evaluating the LCI and LCIA results in terms of completeness, sensitivity, and consistency.

2.2 Building Construction LCA

According to SS-EN 15978 (CEN, 2011) the life cycle of a building is structured into a set of modular stages that define the system boundaries for building LCA. In addition, the standard introduces Module D, which accounts for potential benefits and loads beyond the system boundary, the inclusion of Module D is optional and reported separately.

Product stage

- A1 Raw material extraction
- A2 Transportation from extraction site to manufacturing site
- A3 Manufacturing of the product

Construction stage

- A4 Transportation to construction site
- A5 Installation of the product

Use stage

- B1 Use
- B2 Maintenance
- B3 Repair
- B4 Replacement
- B5 Refurbishment
- B6 Operational energy use
- B7 Operational water use

End of life stages

- C1 Deconstruction and demolition
- C2 Transportation to waste processing site
- C3 Waste processing
- C4 Disposal

Benefits and loads beyond the system boundary

- D Reuse, recovery and/or recycling potential expressed as net impacts and benefits.

2.3 Environmental Product Declaration (EPD)

An environmental product declaration, EPD, provides reliable, validated environmental data about products and their uses, enabling informed, science-based decisions and encouraging ongoing environmental progress through market incentives. (European Committee for Standardization, 2019). It should be noted that the EPDs are produced by the manufacturer and externally reviewed by third party.

2.4 Product Category Rule (PCR)

Product category rule, PCR, defines rules for developing EPDs. It outlines which life cycle stages and processes are included in an EPD. Furthermore, it includes rules on how to calculate LCI and LCIA in developing an EPD. This determines which construction products are comparable based on the information outlined in the EPD (SS-EN 15804, ISO, 2019).

2.5 Environmental Impact and Impact Categories

Environmental impact refers to a set of quantifiable effects of a certain product, material, and activity on the environment. These impacts are categorized into different categories depending on which pollutant is dominant. Jang et al. (2022) carried out an LCA study for seven construction material categories with a total of twenty-two materials and stated that construction materials contribute to multiple environmental impacts in addition to carbon emissions, indicating in their study that other impact categories need greater attention.

Each environmental category has a key pollutant which dominates in that specific category. Among these key pollutants, there is a reference substance for each category. A reference substance is a benchmark used to determine the potential effect that the other key pollutants would have on the environment. A good example would be the most widely used metric, a kilogram of carbon dioxide (CO_2) equivalent. The metric kg CO_2-eq is used as a benchmark to evaluate the potential global warming impact of GHGs relative to the warming effect of one kilogram of CO_2. (American Institute of Architects [AIA], 2010) The most common environmental categories are discussed below.

2.5.1 Global Warming Potential (GWP)

Global Warming Potential (GWP) has been developed to characterize the change in greenhouse gas (GHG) effect due to emissions and absorptions attributes to humans. The unit for measurement is grams equivalent of CO_2 (American Institute of Architects [AIA], 2010). This impact category measures the potential of GHGs to trap heat in the atmosphere, causing climate change. The key pollutants involved in this process are methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), sulfur hexafluoride (SF_6) among others, which are converted to CO_2-eq (Jang et al., 2022).

In LCA practice, GWP is further subdivided into GWP-fossil, which accounts for emissions from fossil carbon sources; GWP-biogenic, which captures the uptake and release of biogenic carbon; GWP-LULUC, which represents impacts from land use and land use change; and GWP-total, which combines all contributions across these sources. (Jang et al., 2022).

2.5.2 Ozone Depletion Potential (ODP)

The impact category Ozone Depletion Potential, ODP, measures how Chlorofluorocarbons (CFCs) degrade the stratospheric ozone layer, increasing Ultraviolet (UV) radiation on earth. The key pollutants are methyl bromide and methyl chloride among others, where CFC-11 is the reference substance. ODP has a low impact regarding most construction materials, but it is slightly higher for materials that use chemicals such as paints (Jang et al., 2022).

2.5.3 Acidification Potential (AP)

The impact category acidification potential, AP, measures emissions that increase acidity in ecosystems, affecting soil, water, and organisms. The key pollutants are ammonia (NH_3), sulfuric acid (H_2SO_4), nitrogen oxides (NO_x), among others where sulfur dioxide (SO_2) is the reference substance. AP is significantly higher in concrete, rebar, and glass (Jang et al., 2022).

2.5.4 Abiotic Depletion Potential (ADP)

The impact category abiotic depletion potential (ADP) measures the depletion of non-renewable resources as a result of extended use. Aluminum (Al), Cadmium (Cd), Iron (Fe), Gold (Au), Mercury (Hg) are some of the pollutants among others where Antimony (Sb) is the reference substance. ADP is commonly divided into two sub-categories: ADPE, which represents the depletion of mineral and metal elements, and ADPF, which reflects the depletion of fossil fuel resources. This impact category is significant in the production of many construction materials, playing a key role in the manufacture of steel, concrete, glass, and insulation (Jang et al., 2022).

2.5.5 Photochemical Oxidant Creation Potential (POCP)

The impact category Photochemical Oxidant Creation Potential (POCP) measures the formation of ground level ozone, from the reaction of air pollutants with sunlight. The key pollutants involved are benzene (C6H6), carbon monoxide (CO), and ethane among others, where ethylene (C2H4) is the reference substance. POCP impact is higher in cement and concrete (Jang et al., 2022).

2.5.6 Eutrophication Potential (EP)

The impact category eutrophication potential (EP) measures nutrient enrichment in water bodies, which leads to algae growth and as a result leads to oxygen depletion. The key pollutants causing this are nitrates (NO_3^-), ammonia (NH_3) among others, where phosphate ion (PO_4^{3-}) is the reference substance (Jang et al., 2022).

EP is further divided into three sub-categories: EPT, which represents terrestrial eutrophication; EPAM, which represents marine eutrophication; and EPFW, which accounts for freshwater eutrophication. The LCA conducted indicated that this category has a relatively low impact on building materials overall; however, it appears to be higher in board products such as plywood board and gypsum board (Jang et al., 2022).

2.6 Building Materials

Building materials can be broadly categorized into biobased and non-biobased materials. According to Bourbia et al. (2023), for a building material to be classified as biobased, it must consist of biomass originating from plants or animals. Biomass refers to organic matter produced by living organisms, excluding any material resulting from geological or fossil formation. Therefore, building materials that do not meet this criterion can be broadly classified as non-biobased building materials. Accordingly, the main building materials relevant to this thesis are discussed below.

2.6.1 Prefabricated Insulated Concrete Structures

Prefabricated insulated concrete structures are prepared in the form of sandwich structures. This sandwich structure comprises three layers namely concrete with steel mesh, insulation and concrete with steel mesh. Bida et al. (2021) discuss how using insulation between wall elements has increased the popularity of prefabricated concrete systems. Joseph et al. (2019) defines the purpose of these structures as having dual purpose: to effectively transfer structural loads and to provide thermal insulation to the building envelope.

2.6.2 Insulation Materials

Gayake et al. (2020) defines insulation materials as materials that slow down the transfer of heat. The key factor to consider in selecting insulation materials is their thermal properties. The other property that needs to be considered is also their chemical properties. Insulation materials must also have the ability to resist fire, while having chemical resistance when subjected to interaction with other chemicals in the surrounding areas.

According to Gayake et al. (2020) Polystyrene, an organic cellular plastic used for insulation, is primarily manufactured in two forms extruded polystyrene (XPS) and expanded polystyrene (EPS), the former is used in this thesis, as it is applied for the conventional construction. Bourbia et al. (2023) discuss that hemp is a common name for tall growing varieties of the cannabis sativa plant. Among its many applications, one notable product is hemp wool, which is used as an insulation material. Due to its high porosity, hemp wool offers excellent thermal performance.

2.6.3 Timber Products

According to Balasbaneh and Sher (2024), engineered wood refers to a man-made construction product formed by combining small pieces of wood like thin lumber, veneers, or wood particles using adhesives or mechanical fasteners, resulting in a stronger and more resilient material.

Balasbaneh and Sher (2024) noted that different types of mass timber are suited for various structural functions. Some are ideal for walls and slabs, while others are better for beams and columns. Glued laminated timber (GLT), commonly used in multi-story structures, is created by bonding thin wooden layers with strong adhesives, aligning all wood grains in the same direction (Kitek Kuzman et al., 2010). In contrast, cross-laminated timber (CLT) consists of kiln-dried lumber layers stacked with alternating grain directions and joined using formaldehyde-free, high-pressure adhesives. This cross layering provides CLT with greater strength than GLT (Ramage et al., 2017).

Balasbaneh and Sher (2024) highlighted that several additional mass timber variants have been examined in recent studies regarding environmental performance and structural characteristics. This includes dowel-laminated timber (DLT), nail-laminated timber (NLT), laminated veneer lumber (LVL), and plywood. For NLT, solid wood planks are arranged on edge and mechanically fastened using nails, while DLT employs wooden dowels for assembly without the use of adhesives, with all grains oriented in the same direction. Plywood is built by layering thin wood veneers with alternating grain directions, which are then bonded together to form a stable sheet, see Figure 1.

Figure 1 Different types of mass timber products. Adapted from Balasbaneh and Sher (2024); illustration by author.

3 Literature Review

This literature review is carried out to deepen the understanding of agricultural facilities, including the nature of their housing systems, the presence of harsh chemical environments, and the implications these have on building material performance. The review examines materials commonly used in agricultural facilities, wood preservation techniques and their associated health concerns, and comparative studies evaluating biobased and conventional construction materials. It also includes an overview of LCA carried out in agricultural settings and in other building types where conventional materials have been substituted with biobased alternatives, drawing from both global and Nordic studies.

3.1 Materials and Construction in Agricultural Facilities

Koesling et al. (2015) carried out a study on 20 dairy farms in Norway and indicated that agricultural buildings are built as durable structures using reinforced concrete floors and walls, along with steel or mixed structural systems. These materials dominate the structure and are the main contributors to embodied energy.

Campbell et al. (2023) discuss that historically poultry houses were built using timber structures with natural ventilation, however modern construction is following a different approach with steel-portal frame buildings with insulated façade panels and uninsulated concrete floors, relying on mechanical ventilation and heating systems. In addition, Fossum et al. (2009) describe poultry housing system in Sweden that use engineered floor systems, concrete surfaces, and mechanically serviced layouts to support cages, manure handling, and hygiene, reflecting a broader shift toward industrial, material-intensive agricultural buildings.

Although concrete dominates modern agricultural buildings due to its structural durability, its exposure to agricultural indoor environment raises concern. According to Thompson et al. (2014), prolonged exposure of concrete block walls to poultry litter can lead to deterioration due to the presence of ammonia, salts, and moisture. Since litter typically has a higher pH than concrete, it can weaken the material over time. Contact with manure causes a chemical layer to form on the surface, reducing both structural integrity and resistance to cracking. In severe cases, this exposure may result in surface erosion. It is therefore essential to regularly check block foundations for signs of damage and if the deterioration is significant, repairs or full replacement may be necessary.

Similarly, De Belie et al. (2000) discusses how timber deterioration in agricultural buildings is primarily driven by weathering and biological processes. Biological degradation is strongly influenced by moisture levels, which are in turn affected by ambient humidity. Elevated humidity increases the likelihood of condensation, thereby raising the wood's moisture content and promoting fungal growth. Although timber naturally has low nitrogen content making it less susceptible to fungal decay exposure to animal urine and manure elevates the nitrogen levels in wood, creating favorable conditions for fungal colonization. In addition, biological damage can also result from insect infestation, bacterial activity, and prolonged contact with nitrates.

Furthermore, De Belie et al. (2000) highlighted environmental risks associated with construction materials in agricultural settings, particularly contamination caused by silage effluent and gases released from livestock waste. The generation of silage effluent is primarily influenced by the moisture level in the forage being ensiled.

The Food and Agriculture Organization of the United Nations (FAO, 1986) noted that timber exposed to environmental elements such as rain and sunlight undergoes continual cycles of moisture uptake and drying. Without adequate protection, this repetitive exposure can result in surface cracking, case hardening (where the outer layer of wood dries faster than inner layer), and warping of the wood grain over time. Preserving the structural integrity of timber is crucial, as deterioration not only necessitates costly material replacement and labor but may also cause operational disruptions during repairs. To enhance durability, design strategies should include the use of larger cross sections, thoroughly dried timber, and construction details that minimize water retention. These include proper ventilation, sloped surfaces to avoid water pooling, overhanging eaves, and damp proofing where timber contacts the soil. Moreover, shielding exposed ends of timber from rain and raising wood posts on concrete bases can help mitigate moisture-related damage. In areas where termite activity is a concern, especially in tropical and subtropical climates, FAO (1986) recommends isolating wooden elements from the ground. This can be done by mounting them on steel or concrete support. Additional preventive measures may include installing termite barriers or applying insecticidal treatments to the soil around the foundation.

According to FAO (1986), timber must be adequately dried either by air seasoning or kiln drying, in which timber is dried in a closed chamber with controlled temperature and relative humidity to accelerate moisture removal, prior to preservative treatment. For effective impregnation, a moisture content of around 25% is considered suitable, although lower moisture levels are preferable for surface applications.

Bansal et al. (2024) discuss recent wood preservation techniques, which are based on nanotechnology:

- impregnation of nanoscale biocides,
- controlled release of preservatives using nanocarriers, and
- wood modification using nanomaterials.

In addition, according to FAO (1986), a good preservative should:

- not corrode metal fasteners,
- be odorless,
- be colorless,
- be water-repellent,
- be suitable for painting or gluing,
- be cost-effective and widely accessible.

De Belie et al. (2000) categorized wood preservatives into four primary types: oil-based, non-fixed water-soluble, fixed water-soluble, and organic solvent-based preservatives.

Oil Based Preservative

FAO (1986) discusses that creosote oil as a common oil-based preservative, which is derived from coal tar and offers reliable protection against fungal decay, termites, and wood-boring insects. It is known for its deep penetration clearly visible in treated wood and its resistance to leaching and evaporation. Creosote also reduces damage from moisture changes and splitting and does not corrode metal fasteners. However, its strong odor and messy application process make it unsuitable for residential use, particularly where painting is required.

Richardson (2002) expressed health concerns related to carcinogenic compounds such as benzopyrenes, which have prompted increased scrutiny. These risks can be mitigated by using creosote distilled at higher temperatures, which lowers the benzopyrene concentration. Similarly, Petersen and Solberg (2005) noted that creosote-treated wood can pose toxic risks to both human health and the surrounding environment. In addition, according to the Swedish Chemicals Agency (Kemi, 2024) the use of creosote is strictly regulated in the European Union (EU) under Registration Evaluation Authorization and Restriction of Chemicals (REACH) regulation and Biocidal products regulation, with specific industrial use.

Non-fixed Water-soluble Preservatives

According to Anderson et al. as cited in De Belie et al. (1997), several non-fixed water-soluble preservatives are frequently used to protect timber, including borax, boric acid, sodium pentachloro phenate, copper sulfate, mercuric chloride, sodium fluoride, and zinc sulfate. Among these, boron-based treatments are especially effective in preventing fungal and insect attacks. However, because these compounds are not chemically bound to the wood, they are unsuitable for use in environments where the wood will be exposed to moisture or direct soil contact.

Fixed Water-soluble Preservatives

Richardson (2002), explained that fixed water-soluble preservatives, commonly applied in outdoor settings, typically include a combination of copper, chromium, and arsenic salts known collectively as CCA. Timber treated with CCA has shown long-term effectiveness in resisting both fungal degradation and insect attacks, even under severe environmental exposure. In this formulation, copper primarily protects the cellulose component of the wood, while chromate ions contribute to the preservation of lignin.

Liese (1987), as cited in De Belie et al. (2000), noted that water-based wood preservatives lacking chromium are generally vulnerable to leaching when exposed to rainfall or soil moisture. In contrast, formulations that include chromium become significantly more leach-resistant after undergoing a fixation period of approximately four weeks.

De Belie et al. (2000) pointed out that a major concern with certain preservative salts is their inherent toxicity, particularly those containing arsenic. Because of the potential health risks, arsenic-based treatments are not advised for use in livestock facilities. There have been reported cases of cattle poisoning resulting from the ingestion of treated fence posts and utility poles. These incidents often occur in regions where animals suffer from salt deficiencies. Such risks can therefore be mitigated by ensuring animals have access to appropriate salt supplements and by applying only preservatives that are securely fixed within the timber. Due to these health and environmental concerns CCA has been banned in EU (Decontamination Institute, 2024)

Organic Solvent Preservatives

De Belie et al. (2000) explained that organic solvent-based wood preservatives typically consist of about 10% active ingredients dissolved in a volatile organic carrier such as petroleum distillate. The low viscosity of these solvents allows for effective surface treatment methods, including brushing, spraying, or short-term immersion. Commonly used preservatives in this group include pentachlorophenol, lindane, dieldrin, tributyl tin oxide (TBTO), copper 8-quinolinolate, and copper naphthenate.

De Belie et al. (2000) reported that treating wood with urea and ureolytic bacteria such as *Proteus* species and *Bacillus* species significantly slowed down biodegradation. This antifungal effect was attributed to the ammonia generated through bacterial activity and the elevated pH levels that resulted in creating an environment unfavorable for wood-decaying fungi. These findings suggest that the presence of ammonia in livestock buildings may actually help suppress fungal deterioration of wood. Additionally, Ejechi and Akpomedaye (1998) demonstrated that a combination of *Proteus* sp. and *Trichoderma viride* not only inhibited fungal growth but also exerted a fungicidal effect. This was credited to the synergistic action of the alkaline pH from ureolysis and the antifungal compounds released by *T. viride*.

De Belie et al. (2000) emphasized that, beyond designing for durability, consistent maintenance plays a crucial role in prolonging the service life of wooden structures particularly in agricultural settings. In animal housing, thorough cleaning and disinfection are essential. It is important to select disinfectants that have been proven to be effective in reducing microbial contamination on timber surfaces. According to the findings, proper cleaning procedures can lower the surface bacterial load by a factor of 1,000, and subsequent disinfection can reduce it by another factor of 1,000 per cleaning.

Animal welfare is a critical consideration in the design of animal housing. For instance, Fossum et al. (2009) investigated causes of mortality of laying hens in Sweden between 2001 to 2004 based on necropsies of 914 hens obtained from National Veterinary Institute (NVA). Four housing systems were investigated, which are single-tiered floor systems with manure bins, with or without regular removal of manure, multi-tiered floor systems with litter belts for regular removal of manure, conventional battery cages, and furnished cages (cages with perches, nests and dust bathing areas). The results indicate that the incidence of disease varies depending on the type of housing system. The study primarily focused on housing system type and management conditions and did not assess the influence of construction materials on hen mortality (Fossum et al., 2009).

3.2 Comparative Review of Biobased and Conventional Building Materials

3.2.1 A Review in Scandinavia the Case of Norway and Sweden

Petersen & Solberg (2005) carried out a cutting-edge review of quantitative studies from Norway and Sweden on the environmental effects of replacing materials with wood. All the studies under review used LCA as a method to assess the environmental impact.

Mørkved & Opdal (1990), as cited in Petersen & Solberg (2005), analyzed the energy use involved in the extraction and production of materials for frames, roofs, and wall constructions. Their study indicated that the results were influenced by the geographical location of the manufacturing facilities, whereas the electricity used for production has low carbon impact. Steel production data were based on ore-based processes in Germany, the data for wood products were from Norway. The study shows that wood-based constructions consumed approximately 40-85% less embodied energy than similar steel structures, about 70-87% less embodied energy than those made of concrete.

Fossdal (1995), as cited in Petersen and Solberg (2005), conducted a comparative study regarding GWP on two wooden single-family houses and two lightweight aggregate concrete block wall single-family houses. The study evaluated energy use and environmental impacts associated with material production over a 50-year lifespan, which included replacement and maintenance. The findings demonstrated that wooden structures required 41% and 46% less energy during the material production phase compared to the concrete alternative. Furthermore, the wooden buildings showed significantly lower emissions: CO_2 emissions were reduced by 56% and 51%, SO_2 by 69% and 65%, NO_x by 34% and 38%, and dust emissions by 40% and 46%, respectively, per square meter of wall area.

Kristensen (1999), as cited in Petersen and Solberg (2005), conducted a comparative LCA of a warehouse frame constructed from laminated wooden construction, glulam, with alternatives in steel and concrete. The system boundary extended up to the end of the use stage just before demolition (i.e., excluding deconstruction and waste management stages). The study faced limitations due to restricted access to production data for steel and concrete, leaving the allocation across life cycle stages unspecified. Although electricity usage was included for steel and concrete manufacturing, the type of energy carrier was not disclosed. The results indicated that, in terms of GWP measured as CO_2-eq, the glulam structure produced 58% less emissions than the steel frame and 64% less than the concrete frame. However, GLT did not outperform all environmental categories. It performed better in acidification potential compared to both steel and concrete. For eutrophication, glulam was superior to concrete but inferior to steel. In terms of photochemical ozone (photo-oxidant formation), it performed better than steel but worse than concrete. The study highlights that while glulam is favorable in terms of GWP and some impact categories, its performance varies depending on the specific environmental indicator.

Petersen and Solberg (2002) conducted LCA comparing steel and glulam beams used in roof construction, with the functional unit defined as one square meter of roof surface. The analysis included the manufacturing phase and waste handling. The study found that the production of steel beams required twice the amount of energy compared to glulam beams. Regarding GHG emissions, the production of glulam resulted in only one-fifth of the emissions produced by steel. Additionally, the waste management strategy significantly influenced the total GHG emissions. When glulam is incinerated and the resulting energy is used to replace fossil fuels, net emissions are reduced. However, if glulam is disposed of in landfills, methane emissions from anaerobic decomposition can lead to substantially higher GHG impacts. The net GHG emissions associated with one square meter of roof surface were estimated to be in the range of 45-57 kg CO_2-eq. These results were sensitive to assumptions such as the discount rate, the source of steel (ore-based or recycled), the fate of wood waste, and whether carbon fixation on regenerated forest land was included.

Petersen and Solberg (2005) reported that substituting steel and concrete with wood in construction can significantly reduce GHG. Specifically, the replacement of steel with wood results in a reduction of approximately 0.06 – 0.88 kg CO_2-eq per kilogram of timber, while substituting concrete with wood leads to a reduction of around 0.16 – 1.77 kg CO_2-eq per kilogram of timber. However, the study also emphasized that certain wood treatments, particularly those involving chemical preservatives, can pose environmental and health hazards, potentially affecting both human well-being and surrounding ecosystems.

According to Petersen and Solberg (2005), all the studies reviewed indicated that wood products have a significantly lower environmental impact in terms of GWP when they are not disposed of in landfills. This highlights the importance of end-of-life treatment in determining the overall sustainability of wood. The way wood is managed after its useful life plays a critical role in minimizing emissions.

3.2.2 Global Systematic Review

Balasbaneh and Sher (2024) conducted a comprehensive global review of the life cycle sustainability assessment (LCSA) of various engineered timber products, with a particular focus on CLT, GLT, and LVL. Engineered wood refers to a class of composite construction materials made by joining layers of thin lumber, veneers, or wood particles using structural adhesives or mechanical fasteners. These materials are designed to enhance strength and durability. The suitability of each product type varies depending on its application. GLT and LVL are often used in load-bearing elements such as beams and columns, whereas CLT is commonly applied in wall and floor systems. The studies reviewed were conducted across multiple countries, including the United States, Sweden, China, and Australia, and utilized LCA software tools such as SimaPro, GaBi, OpenLCA, and ATHENA for environmental and cost assessments.

In their systematic review, Balasbaneh and Sher (2024) highlighted that most studies emphasize environmental and economic analyses, namely LCA and Life Cycle Costing (LCC), while the social dimension of LCSA is largely overlooked. Notably, none of the 93 studies included in the review carried out a complete LCSA incorporating social, environmental, and economic factors. The authors proposed a research framework to guide future investigations in identifying the most sustainable options among engineered timber products. Their review covered global studies, with significant contributions from countries such as the United States, Australia, China, and several European nations. The distribution of analyzed wood products revealed that CLT accounted for 62% of the studies, followed by GLT at 17%, LVL at 9%, Plywood at 8%, and other engineered products such as DLT, NLT, Oriented Strand Board (OSB), and Parallel Strand Lumber (PSL) comprising the remainder.

United States

Chen et al. (2019) conducted an LCA study on CLT in the United States. Their analysis placed particular emphasis on the transportation phase, identifying it as a significant contributor to the overall environmental footprint of CLT production. The study reported that producing one cubic meter of CLT generated a GWP of 155.65 kg CO_2-eq. In addition to GWP, the study also quantified other environmental impact categories, reporting an AP of 1.44 kg SO_2-eq, EP of 0.11 kg PO_4^{3-}-eq, and ODP of 4.13×10^{-6} kg CFC-11-eq. Similarly, Greene et al. (2023) in the United States evaluated steel-framed buildings against timber alternatives utilizing CLT and GLT, concluding that steel structures exhibited higher GWP.

According to Balasbaneh and Sher (2024), CLT has been one of the most extensively studied engineered wood products in recent literature, often examined in comparison to GLT. Despite their common use in sustainable construction, these materials serve different structural purposes in multi-story buildings. Studies by Lolli et al. (2019) in Norway and Puettmann et al. (2021) in the United States showed that CLT is typically applied in floor slabs and wall assemblies, while GLT is better suited for structural elements like beams and columns due to its superior load-bearing capacity.

As noted by Balasbaneh and Sher (2024), numerous studies have investigated the integration of mass timber with other structural systems, particularly in hybrid configurations with concrete and steel. For instance, Duan et al. (2022) in China and Pierobon et al. (2019) in the United States examined the environmental performance of hybrid timber-concrete buildings. The research conducted by Pierobon et al. (2019) demonstrated that replacing reinforced concrete with hybrid CLT structures significantly reduces the GWP compared to traditional cast-in-place concrete structures. In another study, Balasbaneh et al. (2018) introduced a composite structural concept in Malaysia that incorporates steel plates alongside GLT or LVL for use in columns and beams. Their results revealed that such hybrid mass timber systems not only emit less CO_2 but are also more economically efficient than conventional concrete-only designs.

China

Guo et al. (2017) conducted a comparative LCA study in China evaluating CLT and reinforced concrete buildings, with a particular focus on energy performance in cold climate regions. The findings indicated that CLT-based buildings demonstrated superior thermal efficiency, achieving nearly 9.9% total energy savings compared to their reinforced concrete counterparts throughout the life cycle of the building. Additionally, the study underscored the potential of CLT to contribute to reduced carbon emissions throughout the building's operational phase.

Duan (2023) conducted comparative LCA of CLT and reinforced concrete buildings situated in China, where the LCA focused across their full-service life. The study concluded that CLT structures offer substantial environmental advantages, making them a highly effective strategy for reducing GHGs emissions in China's construction industry.

Chile

Felmer et al. (2022) conducted LCA in Chile and demonstrated that buildings constructed with CLT and GLT components emitted significantly less CO_2 than conventional concrete structures reporting values of 101 kg CO_2 eq/m² for timber-based construction versus 167 kg CO_2 eq/m² for concrete.

Life Cycle Stages

According to Balasbaneh and Sher (2024), the majority of existing LCA studies on mass timber have concentrated on the product and construction stages (modules A1–A5), with only limited attention given to later life cycle phases. Importantly, no research has yet been identified that evaluates the repair stage (B3). This presents an opportunity for future studies to compare the repair demands of mass timber buildings with those constructed using concrete or steel, and to analyze how different types of timber perform under varying environmental and climatic conditions.

End of Life Stage

Balasbaneh and Sher (2021) analyzed the end-of-life phase of buildings incorporating CLT and GLT, emphasizing that energy recovery from these materials can contribute to lowering overall carbon emissions. Petrovic et al. (2023), in a study based in Sweden, found that reusing timber in construction leads to a substantially reduced embodied carbon footprint compared to the use of virgin materials. Furthermore, Jayalath et al. (2020) in Australia reported that CLT buildings offer economic advantages over reinforced concrete, particularly due to lower costs associated with transportation, deconstruction, and recycling.

European Standard

The World Green Building Council (2022) emphasized the need for future updates to European standards to account for carbon emissions linked to the reuse, recycling, and energy recovery of wood-based construction materials. This highlights the significance of incorporating the benefits and burdens associated with end-of-life processes (module D) when evaluating the environmental performance of mass timber.

Summary

Studies have shown that substituting concrete and steel with timber-based building materials can significantly reduce the GWP of a construction. However, since design requirements largely determine which type of engineered wood product is most appropriate, there is no definitive answer as to which option consistently achieves the lowest GWP. Moreover, existing research tends to focus primarily on the early life cycle stages (A-stages), while the later stages have received comparatively little attention.

3.3 The Concept Barn: The Danish Experience

The Concept Barn was introduced in Denmark in 2019 with primary attention given to minimizing costs and enhancing operational efficiency and stability. According to findings from the initiative "The Climate-Friendly Agricultural Building," the GHG associated with the Concept Barn were estimated to be 26% higher compared to a conventional livestock facility constructed with concrete components (Poulsen, 2024).

Structurally, the Concept Barn features a traditional foundation design consisting of concrete slurry channels. The structure uses steel trusses for support, with prefabricated Polyisocyanurate (PIR)foam panels on the exterior façades. The roofing system is assembled using wooden purlins and covered with corrugated steel sheeting. This configuration also includes thermal insulation, a vapor control layer, and a steel ceiling lining (Poulsen, 2024).

Poulsen (2024) investigated strategies to lower the GHG emissions of the Concept Barn. In collaboration with the Technical University of Denmark (DTU), a LCA was conducted comparing the environmental impact of the Concept Barn and a traditional barn model. The evaluation was carried out using the LCAbyg software developed by BUILD, formerly known as the Danish Building Research Institute at Aalborg University. This tool enabled a cradle-to-grave assessment of GWP, expressed in CO_2-eq/m^2 annually. The analysis specifically considered key structural elements, including the foundation, load-bearing system, roof, and ceiling.

Poulsen (2024) reports that replacing traditional concrete flooring in slurry channels with a plastic membrane yields an 11% reduction in carbon emissions over the operational lifespan of the barn. However, this environmental benefit is contingent on the assumption that the membrane remains intact and suitable for reuse. The assessment presumes the existence of a facility (potentially the manufacturer) that can retrieve, clean, and either directly reuse or granulate the used membrane for future applications. Therefore, this emission reduction is only realized during the membrane's second life cycle. In its initial application, the plastic membrane has a marginally higher environmental impact than concrete, contributing 0.1% more in CO_2-eq.

Replacing the steel-framed load-bearing system in the Concept Barn with timber-based alternatives leads to a substantial reduction in environmental impact, specifically an 86% reduction in emissions from the structural framework alone. This change translates into an overall reduction of 6.4% in the barn's total carbon footprint (Poulsen, 2024). Timber offers the advantage of temporary carbon sequestration, storing CO_2 from the atmosphere until decomposition occurs due to moisture exposure, decay, or combustion. The analysis incorporated two wood-based construction options: GLT and assembled rafters made from construction-grade wood. Both were assessed in terms of emissions and practical implementation. While GLT is structurally stronger, it is considerably more expensive than both steel and traditional rafter timber, which may require closer spacing and double-rafter configurations to meet load-bearing requirements, see Figure 2. (Poulsen, 2024)

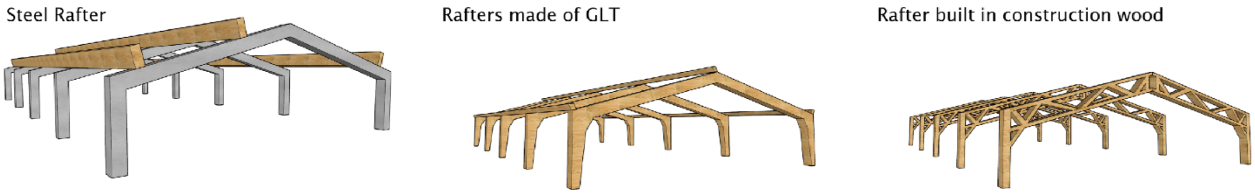

Figure 2 Structural configuration of the steel rafter and corresponding wood-based alternatives used in the Concept Barn. Adapted from (Poulsen, 2024); illustration by author.

Poulsen (2024) conducted a comparative analysis of various roof and ceiling material combinations to evaluate their environmental performance. In the study, the configuration utilizing steel plates for both roofing and ceiling was assigned a reference index of 100. Other material pairings were then benchmarked against this value to determine their relative carbon impact. Combinations yielding an index score below 100 were considered more sustainable, while those exceeding 100 were deemed less favorable. This approach enabled a standardized assessment of GWP across different roof system setups.

The analysis by Poulsen (2024) highlights significant differences in the climate impact of roofing materials. When fiber cement is used for both roofing and ceiling finishes, the GHG emissions from these components can be reduced by as much as 47% compared to the reference setup using steel sheeting. Conversely, the application of Polyisocyanurate (PIR) foam panels increases the carbon footprint by approximately 30%, primarily due to the production and installation characteristics of the material. Similarly, sedum roofing solutions exhibit a higher environmental impact, which is largely attributed to their complex layering system. These systems require a sealed substructure typically composed of bitumen, geotextiles, or similar materials that add to the total embodied emissions.

In the original design of the Concept Barn, PIR-foam panels were chosen for the exterior walls primarily due to their cost-efficiency, being approximately one-third the price of standard precast concrete sandwich panels. However, this material choice comes with a trade-off: a significantly higher carbon footprint. An alternative solution examined in the study involved replacing PIR-foam facade elements with CLT insulated using mineral wool. This substitution yielded a reduction of 4.4% in the overall GHG emissions of the barn. While the climate benefits of CLT are evident, the current market lacks competitive pricing for timber-based facade systems suitable for pig farming. Inquiries made to two Danish suppliers failed to provide definitive cost estimates, indicating that such solutions may not yet be economically viable.

The results of the study by Poulsen (2024) indicate that implementing the suggested material substitutions in Concept Barn's foundation, structural framework, roofing, and wall systems can achieve a cumulative reduction of up to 30% in its overall GHG emission. Notably, these strategies are not limited to the Concept Barn; many of the proposed improvements are also applicable to conventional pig barns. Specifically, replacing the concrete base with a plastic membrane and swapping concrete facade elements with timber-based alternatives in standard barn designs could lead to a carbon footprint reduction of approximately 14%.

4 Methodology

4.1 Overview

In this thesis, comparative LCA is conducted on a poultry facility, contrasting conventional concrete and steel construction with a biobased alternative in which concrete, steel, and selected other materials are substituted with biobased products.

This section begins by defining the goal and scope of the study, followed by discussing the selection and use of software and calculation tool along with the integration method selected for this thesis. Furthermore, a general description of the facility discussing architectural layout and site work with illustrations is presented. During the study in calculating the LCA, two approaches are proposed: the first one is based on product specific EPDs provided by manufacturers, whereas the second one uses generic EPDs that comply with EN 15804+A2 to represent average industry data.

4.2 Goal and Scope Definition

LCA is an iterative process between the four LCA stages, which are the goal and scope definition, inventory analysis, impact assessment and interpretation. The goal of this study is to compare a conventional construction solution with a biobased alternative and to identify key areas of improvement in mitigating carbon impact. The scope of the study focuses on embodied environmental impacts, with particular emphasis on embodied carbon. The system boundary includes the following life cycle stages:

- A1-A3 raw material extraction, transportation to manufacturers, manufacturing
- A4-A5 transportation to construction site, installation
- B4 replacement
- B5 refurbishment
- C1-C4
- D Benefits and loads beyond the system boundary.

The stages that are excluded (B1-B3, B6, and B7) are primarily operational stages, which fall outside the study's scope. These stages do not depend on the construction material choices and therefore do not contribute to the objective of comparing embodied impacts between conventional and biobased construction.

The functional unit for this study is one building with an analysis period of fifty years. The assessment is conducted aligning with ISO 14040/14044 and the EN 15978 framework for environmental performance of buildings. GWP is chosen as the impact category for comparison as it quantifies GHGs in kg CO_2-eq.

4.3 Software and Calculation Tool

In conducting the comparative LCA for this thesis, Autodesk Revit version 2024 and One Click LCA were used. Autodesk Revit is a Building Information Modeling software which was used to create a 3D Building Information Model (BIM) model for the poultry building. On the other hand, One Click LCA is a tool that is used to conduct LCA calculations.

The choice of using One Click LCA over other LCA calculation tools is motivated below:

- It complies with international standards.
- It provides access to the largest EPD database.
- It provides student licenses.
- It has continuous training and expert support.

- It allows manual entry of material quantities when elements cannot be extracted from the Revit model because of modeling complexity.

The integration of One Click LCA to Revit in quantifying the material for LCA calculation is described below:

- Firstly, the 3D model is created in Revit,
- Secondly, using One Click LCA plugin, the desired material is sent to One Click LCA cloud,
- Thirdly, an Excel file containing the extracted material quantities can be generated and downloaded for verification and further processing.
- Fourthly, one can add material quantities when it is not possible to include them in the BIM model, such as urbanite for site work, footing pad, roof truss, and wood stud.
- Finally, a mapping of each material quantity to an EPD and final calculations are performed.

4.4 Architectural Drawing Site Work and Facility Overview

The building is an agricultural facility situated in Borby, Sweden. The facility, which is prefabricated, is used for housing egg laying chickens. The foundation was created by excavating 60 cm and then filling the space with urbanite, which consists of recycled fragments of broken concrete. The use of recycled material is a good approach for sustainability and in reducing environmental impact.

The facility is divided into two main sections. Section one is the employee area for packing and administration. Section two is dedicated to housing the chickens. In Section two, the space is divided into two subsections, labeled A and B as shown in Figure 3. These subsections are separated by a one-meter-high concrete wall, topped with a mesh panel. The mesh prevents the chickens from flying between the sections while allowing full visibility for employees. The chickens are not caged and are free to move around within their designated section. The elevation of the building is presented in Figure 4 while the three-dimensional presentation is shown in Figure 5. An image illustrating the ongoing construction of the facility is presented in Figure 6.

The design and layout of both cases is typical, maintaining functional equivalency. The thermal conductance (U-value) of both conventional and biobased construction has been maintained to meet the Swedish standard.

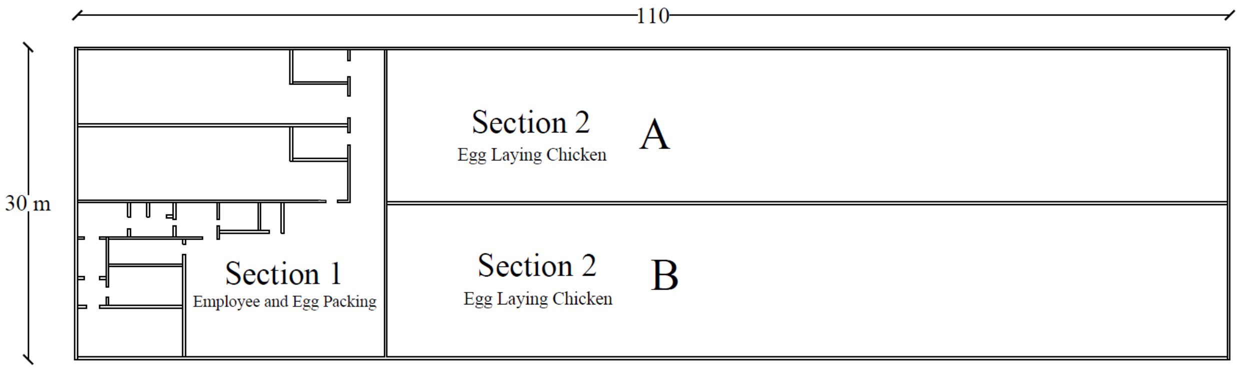

Figure 3 Schematic Illustration of the poultry building. Illustration by author.

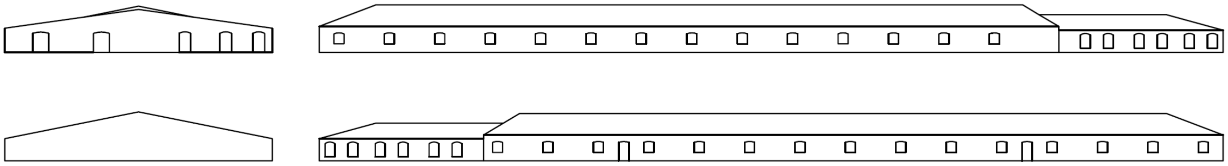

Figure 4 Schematic illustration of front elevation (top left), rear elevation (bottom left), left elevation (top right) and right elevation (bottom right). Illustration by author.

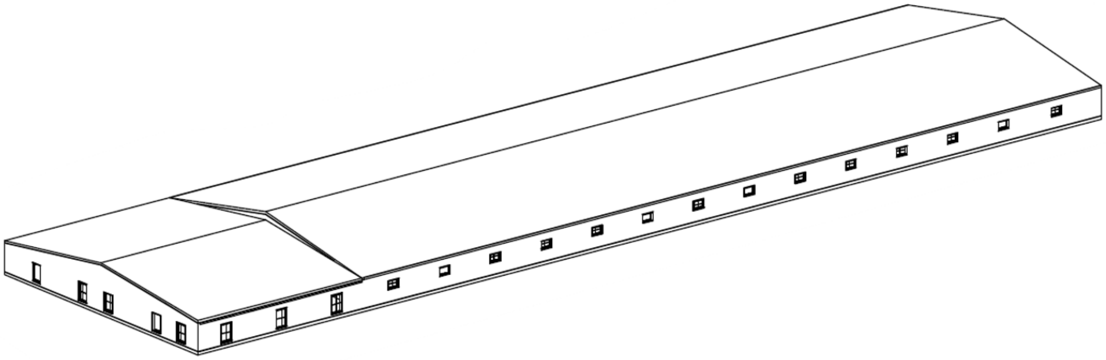

Figure 5 3D representation of the poultry facility. Illustration by author.

Figure 6 The poultry building under construction in Borby Sweden which is used as an example for Conventional construction in concrete and steel. Photograph taken by author.

4.5 Case Description

4.5.1 Conventional Construction

The walls in Section One primarily consist of workstation partitions and exterior prefabricated insulated concrete panels. These exterior walls feature multiple ventilation shafts, windows, and door openings distributed across the building envelope. The prefabricated concrete panels are manufactured in various lengths, i.e., 6.02 m, 6.74 m, and 4.91 m, each with different configurations of openings, resulting in variations in their overall weight. In total, 46 prefabricated exterior wall panels are used in the building. The height of these walls differs between sections: 2.70 m for Section one and 3.15 m for Section two.

4.5.2 Biobased Construction

Beyond replacing concrete and steel with timber alternatives, this study also introduces design features that are characteristics of agricultural buildings, especially those related to the challenging indoor environment found in animal housing.

Since timber products are vulnerable to high moisture levels, ammonia and chemical exposure, which is typical in poultry barns, the biobased construction includes protective strategies to ensure durability and hygiene. The strategies included in this case are:

- Installation of cladding to withstand high-pressure water cleaning, which is common in animal barns for sanitation purposes.
- The cladding also helps to withstand chemical exposure such as ammonia. The cladding suggested is Fiber Reinforced Polymer (FRP) panels.
- Installation of vapor barrier on the warm side to limit moisture penetration into structural timber components.

4.6 Thermal Transmittance (U-value) In Maintaining Functional Equivalency

Thermal transmittance (U-value) is defined as the amount of heat transfer per unit area and per unit temperature difference between the two sides of a material under steady-state conditions (Aguilar-Santana et al., 2020). It is widely used to characterize the thermal performance of building components. Hence, this thesis utilizes this concept to maintain functional equivalency between the two cases under study.

Hörndahl (2008) reports that typical U-values for the walls, roofs, and floors of numerous cattle, pigs and poultry facilities range between 0.22 and 0.35 W/m^2. This was verified while modeling the building components in Autodesk Revit. However, Revit does not present thermal performance of building components in U-value, but rather in thermal resistance (R-value) which is the inverse of the former.

4.7 Approach One: Manufacturer Specific EPD

This approach is based on the availability of the EPD for conventional construction in the One Click LCA database. The manufacturer for the prefabricated concrete structures is Benders Byggsystem AB. A simple search under One Click LCA platform to map a material to an EPD with "Benders" as a keyword revealed its availability in the database. Such EPDs are prepared considering the building element, such as a wall or slab as being a composite material, whereas in Autodesk Revit a 3D BIM modeling software considers the wall as a layered structure.

For example, the exterior wall has three layers namely concrete with steel mesh, insulation and another layer of concrete with steel mesh. In Revit, the wall is modeled accordingly, with each layer assigned the correct thickness and material properties to achieve the required thermal performance. However, when exporting materials, these layers are listed separately rather than as an aggregated component. As a result, it was determined that the material quantities exported from Revit needed to be combined in order to match the formats used in the manufacturers' EPDs. This approach to aggregation was adopted for all similar cases.

Additionally, for materials not manufactured by Benders, as well as for the biobased construction option, specific EPD selection criteria had to be developed. These criteria were established based on relevance, meaning that the selection of EPDs considered the following relevance factors:

- Product relevance, meaning whether the EPD represents a composite product or not. Since the material quantities are aggregated and mapped to a single EPD, any EPDs that do not correspond to a composite wall or slab system are excluded.
- Geographic relevance: which is considered because it influences the transportation impacts in the LCA. The geographic relevance is prioritized in the following order: Sweden first, then the Scandinavian region, and finally Europe.

- Data availability regarding thermal performance: Not all EPDs report on thermal performance. Since functional equivalency must be maintained, and U-values need to be calculated, the availability of such data is essential.
- System Boundary: The life cycle stages covered by the EPD are considered to ensure alignment with the stages used in this thesis.
- PCR compliance: This criterion assesses whether two EPDs are comparable. If EPDs are based on different PCRs, they cannot be compared because they follow different methodological guidelines for calculating environmental impacts.

After compiling all the necessary information, Approach One was tested. In the One Click LCA platform, the database was filtered using the search term “Benders”, which returned several products. Among these, two prefabricated insulated concrete wall EPDs and two prefabricated slab EPDs were found and considered potentially relevant. However, one of the key relevance criteria is that the inclusion of U-value was missing from these EPDs. As a result, Benders was excluded from the EPD selection.

Additional search terms, such as “prefabricated insulated concrete wall”, were then used to identify other EPDs that might satisfy the relevance criteria. For clarity, the relevance criteria and corresponding remarks are presented below. Similarly, for the biobased alternative, search terms such as “prefabricated biobased wall”, “biobased”, and “timber” were used to filter the database.

A thick “✓” mark is placed if it fulfills the relevance criteria, “✗” mark is placed if it does not and a “-” mark if the criterion is not reported in the EPD. The prefix Such as RTS, S-P, HUB, etc., under the EPD number in Table 1 and Table 2 indicates under which EPD program it was developed. The assessment presented in Table 1 refers to prefabricated insulated concrete wall systems, while Table 2, presents the corresponding assessment for prefabricated insulated biobased wall systems.

4.7.1 Exterior Wall Conventional Construction

Table 1 EPD assessment based on relevance criteria for conventional construction.

EPD Number	**Relevance**					**Remark**
	Product type	Geography	PCR	System boundary	U-Value (W/m^2. K)	
RTS_125_21	✓	✓	EN 15804+A2, RTS PCR	✓	0.3	Meets all criteria
S-P-08660	✓	✓	EN 15804+A2, PCR 2019:14	✓	0.18	Thickness of the wall needs to be increased to fulfill the required Swedish U-value.
HUB-1678	✓	✓	EN 15804+A2	✓	-	Additional information required
NEPD-6217-5481-EN	✓	✓	EN 15804+A2: NPCR 020:2021 Part B	✓	-	Additional information required

NEPD-6220-5482-EN	✓	✓	EN 15804+A2: NPCR 020:2021 Part B	✓	-	Additional information required

4.7.2 Exterior wall Biobased Construction

Table 2 EPD assessment based on relevance criteria for biobased construction.

EPD Number	**Relevance**					**Remark**
	Product type	Geography	PCR	System Boundary	U-Value (W/m^2)	
HUB-1642	✓	✓	EPD Hub Core PCR v1.1, EN 15804+A2: 2019	✓	0.18/0.15/0.13	Meets requirement partially
NEPD-8386-7946-EN	✓	✓	EN 15804:2012+A2:2019, Part B Curtain Walling	✓	0.2 – 0.25	Thickness of the wall needs to be increased to fulfill the required Swedish U-value.
EPD-IES-0002561	✓	✓	PCR 2019:14 Construction product v1.3.4, EN 15804+A2:2019, ISO 14025	✗	-	Additional information required

4.7.3 Transition from Approach One to Approach Two

Approach one followed two main paths, which are using manufacturer EPD and aggregating the material quantity exported from the Revit model to one single value that can be mapped to one specific EPD. The extensive effort invested in filtering the One Click LCA database proved to be unproductive. A significant challenge encountered was the inconsistency in the PCRs followed by various EPDs within the database. Since conducting a reliable LCA requires EPDs to adhere to a common PCR framework, it was deemed methodologically unfeasible to proceed with datasets based on mismatched PCRs. Consequently, an alternative approach became necessary.

One Click LCA offers a collection of generic EPDs, which, although not available for external download, are integrated for use exclusively within the platform. To maintain consistency and comparability, a more focused filtering process was developed, emphasizing these generic datasets. According to Udas (2025), unless otherwise specified, these generic EPDs are developed in accordance with the EN 15804+A2 standard, which serves as the primary PCR reference for their environmental impact assessments. This ensured a harmonized basis for evaluating materials and facilitated the continuation of the study under a consistent methodological framework. Thus, the second approach was developed.

4.8 Approach Two: Generic EN 15804+A2 Compliant EPD

The second approach uses generic EPDs found within the One Click LCA database. The relevance criteria placed in the first approach are taken into consideration in the second approach. However, generic EPDs lack detailed information such as U-value and system boundaries, showing the impact in each stage. Rather, it mentions its GWP stages (A1-A3). Out of the five relevance criteria, three are valid; product relevance, geographic relevance and PCR. Hence, the following life cycle inventory is determined based on this approach.

Literature was used as the basis of assumption regarding structural integrity in substituting conventional construction to biobased construction in order to carry out the LCA calculation. Furthermore, values such as density are taken from the respective generic EPDs. The EPDs used are summarized in a table and added in Appendix B.

4.9 Life Cycle Inventory

4.9.1 Subsurface for Conventional and Biobased Construction

The sub surface has been prepared by excavating 60cm of soil and refilling it with urbanite. Key words such as "urbanite", "reclaimed" and "reclaimed concrete" are used to filter out the generic EPD database. However, there was no result for urbanite, hence crushed stone is used instead. The density entered was the value declared in the generic EPD, see Table 3.

Table 3 Material quantity for both constructions' subsurface.

Material	Volume ($m^{3)}$	Density (Kg/m^3)	Quantity (kg)	EPD Program	Country of Origin
Crushed stone	1 980	1 320	2 613 600	OKOBAUDAT	Germany

4.9.2 Prefabricated Insulated Footing Pad for Conventional Construction

According to the drawing document provided, the construction consists of 80 footing pads, each with a size of 1.2 m x 1.2 m. To simplify modeling and save time, a single-footing pad was modeled as a layered structural slab in Autodesk Revit 2024. The material quantity extracted from this single model was then multiplied by the total number of footings.

Relevant literature was reviewed to determine the appropriate steel diameter and spacing for reinforcement. Yuan et al. (2021) investigated a cost-effective method of rebar spacing, using 12 mm steel bars arranged at 127 mm x 127 mm in their study. The materials used is listed in Table 4.

Table 4 Material quantity for the conventional construction footing pad.

Material	Volume (m^3)	Density (kg/m^3)	Quantity (kg)	EPD Program	Country of Origin
Concrete	25.6	2 369	60 646	One Click LCA	Sweden
XPS	8.0	33	264	One Click LCA	Sweden
Steel reinforcement	0.2	7 850	1 570	OKOBAUDAT	Germany

4.9.3 Prefabricated Insulated Footing Pad for Biobased Construction

Since XPS is not a biobased insulation material, the biobased alternative replaces it with hemp wool insulation. Hemp wool is not included in Autodesk Revit's Default material library; therefore, the material was downloaded from bimobject.com, and its properties were applied in Revit to maintain the required thermal conductance (U-value). According to BIMobject (2025), Biofib' Chanvre is an insulation material made from hemp fiber which is recommended for wooden frame structures. This makes it suitable for biobased construction. The materials used in the biobased construction are listed in Table 5.

Table 5 Material quantity for the biobased construction footing pad.

Material	Volume (m^3)	Density (kg/m^3)	Quantity (kg)	EPD Program	Country of Origin
Concrete	25.6	2 369	60 646	One Click LCA	Sweden
Hemp wool	8.0	35	280	One Click LCA	Sweden
Steel reinforcement	0.2	7 850	1 570	OKOBAUDAT	Germany

4.9.4 Prefabricated Insulated Concrete Slab for the Conventional Construction

Joseph et al. (2019) investigated the flexural behavior of insulated concrete sandwich panels, their load-bearing capacity, cracking behavior, and deformability. They used two mesh arrangements of 50 mm x 50 mm and 100 mm x 100 mm with a wire dimension of 2.2 mm. The study revealed that the 50 mm x 50 mm showed distributed cracking, higher ductility and better energy dissipation whereas the 100 mm x 100 mm failed due to widening of single crack, which indicates lower ductility.

The conventional construction follows a similar construction technique and has a gross floor area of 3,300 m^2. Given that such facilities are moisture-sensitive and frequently subjected to high-pressure water cleaning, the same slab configuration will also be applied in the biobased construction, see Figure 7. The material use for the ground slab is presented in Table 6.

Table 6 Material quantity for the conventional construction ground slab.

Material	Volume (m^3)	Density (kg/m^3)	Quantity (kg)	EPD Program	Country of Origin
Concrete	1 450.3	2 369	3 435 761	One Click LCA	Sweden
XPS	527.4	33	17 391	One Click LCA	Sweden
Steel reinforcement	1.0	7 850	7 929	OKOBAUDAT	Germany

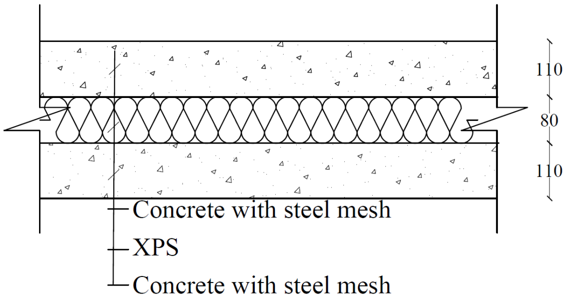

Figure 7 Slab section showing the material layout (cm).

4.9.5 Prefabricated Insulated Concrete Slab for the Biobased Construction

The difference between the concrete slab for conventional and biobased construction is the insulation used. The conventional construction uses XPS whereas in the biobased construction, the XPS insulation was replaced by hemp wool, as presented in Table 7.

Table 7 Material quantity for the biobased construction ground slab.

Material	Volume (m^3)	Density (kg/m^3)	Quantity (kg)	EPD Program	Country of Origin
Concrete	1 450.3	2 369	3 435 761	One Click LCA	Sweden
Hemp wool	527.4	35	18 459	One Click LCA	Sweden
Steel reinforcement	1.0	7 850	7 850	OKOBAUDAT	Germany

4.9.6 Exterior Wall for the Conventional Construction

The exterior wall of the conventional construction is a prefabricated, insulated concrete wall. Relevant literature was reviewed to determine the appropriate diameter and spacing of steel reinforcement. Bida et al. (2021) describe the use of 6 mm steel wires spaced at 100 mm as reinforcement within concrete layers, see Figure 8. These values were adopted for the LCA calculations and to ensure compliance with the Swedish U-value requirements for agricultural facilities. The materials used are listed in Table 8.

Table 8 Material quantity for conventional construction exterior wall.

Material	Volume (m^3)	Density (kg/m^3)	Quantity (kg)	EPD Program	Country of Origin
Concrete	123.4	2 369	292 263	One Click LCA	Sweden
XPS	77.1	33	2 544	One Click LCA	Sweden
Steel reinforcement	0.9	7 850	6 751	OKOBAUDAT	Germany

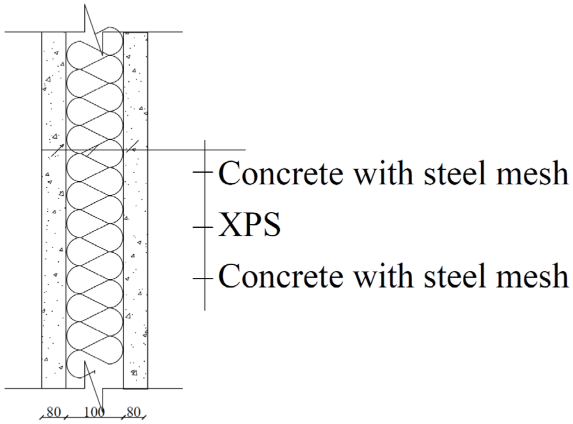

Figure 8 Prefabricated insulated concrete wall section showing the material layout (cm).

4.9.7 Exterior Wall for the Biobased Construction

In the conventional construction, the exterior wall functioned as a load-bearing structure; therefore, no separate load-bearing columns were required or calculated. In contrast, for the biobased construction based on the literature reviewed in Section 3, GLT was selected as the structural load-bearing column material.

The wall assembly in this context must withstand high-pressure water washing, elevated moisture levels, and chemical exposure such as ammonia. Failure to meet these requirements can lead to reduced material durability and potential health risks. To address the demanding conditions, present in animal housing facilities, this thesis proposes a wall structure with a vapor barrier integrated on the warm side of the structure, see Table 9. In addition, FRP wall cladding is installed on the interior surface to resist moisture, ammonia exposure, and high-pressure water washing, see Table 10. According to Citadel Architectural Products (n.d.), the EnviroGuard LUA wall cladding, which is a composite of FRP or polyethylene facing bonded to a luaun substrate, is suitable for use in animal housing facilities as presented in Figure 9. The calculation details are provided under Appendix A.1 Supporting Calculation for Section 4.7.2 Exterior wall Biobased Construction.

Table 9 Material quantity for the biobased construction exterior wall (m^2).

Material	Area (m^2)	Density (kg/m^2)	Quantity (kg)	EPD Program	Country of Origin
Vapor barrier	762	0.14	107	One Click LCA	Sweden

Table 10 Material quantity for the biobased construction exterior wall (m^3).

Material	Volume (m^3)	Density (kg/m^3)	Quantity (kg)	EPD Program	Country of Origin
Wood panel	17.0	440	7 480	One Click LCA	Sweden
Wood studs 28 mm x 70 mm	4.9	440	2 156	One Click LCA	Sweden
CLT Panel	24.6	481	11 833	One Click LCA	Sweden
Hemp Insulation	70.2	35	2 457		
Wood studs 45 mm x 90 mm	10.0	440	4 440	One Click LCA	Sweden
FRP Cladding	0.7	1 350	918	EPD Italy	Italy

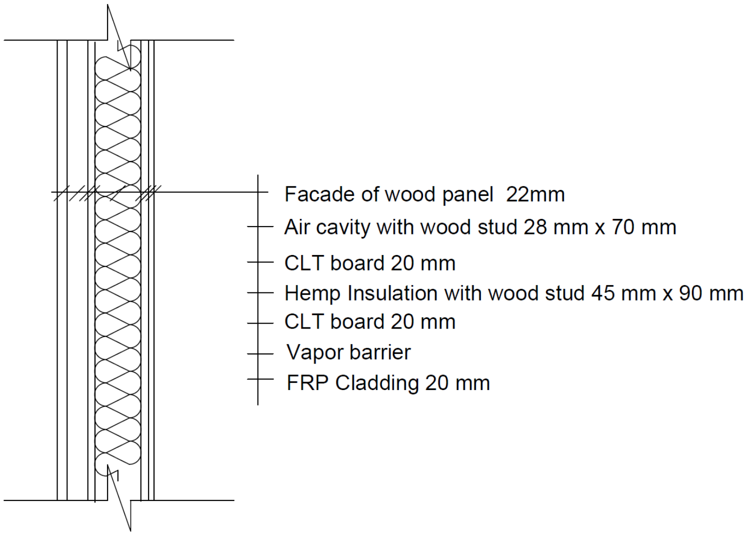

Figure 9 Exterior wall section for the biobased construction.

4.9.8 Interior Wall for the Conventional Construction, Type 1

The interior wall is located in Section two, where the egg laying chickens are housed, (see Figure 3). It has a height of one meter dividing the egg laying area into two sections. The remaining height above the wall is enclosed with a mesh, which allows visibility for employees while preventing the hens from moving between the sections. At both ends of the wall, doors provide access for staff to move between the two areas.

The calculation of this prefabricated concrete wall is based on the literature referenced in section 4.9.6 Exterior Wall . However, the key difference in this case is that the wall is uninsulated and consists solely of concrete and steel, see Table 11. It has a thickness of 0.12 m and a length of 87 m.

Table 11 Material quantity for the conventional construction interior wall Type 1.

Material	Volume (m^3)	Density (kg/m^3)	Quantity (kg)	EPD Program	Country of Origin
Concrete	10.44	2 369	24 732.36	One Click LCA	Sweden
Steel reinforcement	0.04	7 850	314	OKOBAUDAT	Germany

4.9.9 Interior Wall for the Conventional Construction, Type 2

This interior wall separates section one from section two. It is a prefabricated, insulated concrete wall. Although it is classified as an interior wall, its construction method is similar to that to the exterior wall described for the conventional construction. Insulation is required due to the temperature difference between the two sections.

The wall has a total length of 29.5 m, a height of 3.2 m, and a thickness of 0.26 m. It comprises three layers namely concrete with steel reinforcement mesh, insulation and concrete with steel reinforcement mesh. Based on the above-mentioned assumptions, the material quantity is presented in Table 12.

Table 12 Material quantity for the conventional construciton interior wall Type 2.

Material	Volume (m^3)	Density (kg/m^3)	Quantity (kg)	EPD Program	Country of Origin
Concrete	14.90	2 369	35 298	One Click LCA	Sweden
XPS	9.30	33	307	One Click LCA	Sweden
Steel reinforcement	0.04	7 850	314	OKOBAUDAT	Germany

4.9.10 Interior Wall for the Conventional Construction, Type 3

This wall is located in section one, which is the employees' section, see Table 13. The supporting calculation is provided in Appendix A.2 Supporting Calculation for Section 4.9.10 Interior Wall for the Conventional Construction, Type 3.

Table 13 Aggregated volume for Lindab sandwich wall and density from One Click LCA EPD database.

Material	Volume (m^3)	Density (kg/m^3)	Quantity (kg)	EPD Program	Country of Origin
Lindab Antique	35.80	30.92	1 106.94	Utena Plant	Lithuania

4.9.11 Interior Wall for the Biobased Construction, Type 1

This wall, which serves as a divider between the two egg-laying sections, has been substituted with biobased alternative. It consists of a lightweight wood-frame structure clad with CLT as presented in Table 14. However, because this area is exposed to high moisture levels and chemical agents, additional FRP cladding is proposed to enhance durability. The final wall assembly therefore consists of wood studs measuring 45 mm x 90 mm, a CLT and an interior layer of FRP cladding see Figure 10.

Table 14 Material quantity for biobased construction interior wall Type 1.

Material	Volume (m^3)	Density (kg/m^3)	Quantity (kg)	EPD Program	Country of Origin
Wood stud	1.30	440	572	One Click LCA	Sweden
CLT panel	0.35	481	168	One Click LCA	Sweden
FRP cladding	0.52	1 350	702	EPD Italy	Italy

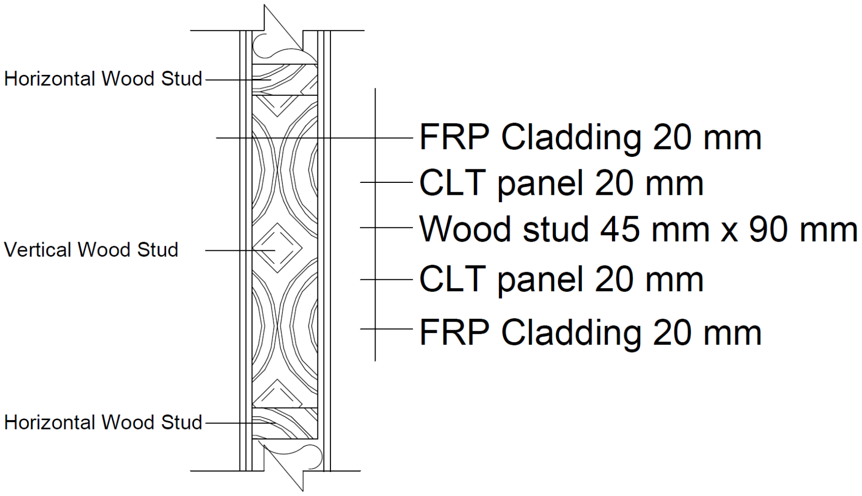

Figure 10 Wall section for biobased construction interior wall Type 1.

4.9.12 Interior Wall for the Biobased Construction, Type 2

This wall separates the employee area from the egg laying section. In the conventional construction, it followed the same build-up as the exterior wall and functioned as a load-bearing element. In the biobased alternative, the structural requirements outlined in Section 4.9.7 Exterior Wall were considered. Since all load bearing GLT elements have already been calculated and accounted under the exterior wall, this wall no longer needs to carry structural loads and is therefore designed solely as a non-load bearing partition,

Hence, the wall consists of 45 mm x 90 mm wood studs, a CLT panel, hemp wool insulation, and FRP cladding as presented in Table 15. It has a total length of 29.5 m, a height of 3.2 m, and a total thickness of 0.098 m, see Figure 11. The vertical studs are spaced at 0.6 m (center-to-center). For the horizontal studs, it is assumed that they run continuously along the full length of the wall, and no deductions are made at the intersections with the vertical studs, A total of four horizontal studs is assumed: one at the top, one at the bottom, and two intermediate rails. Based on the wall length the stud spacing, the number required vertical studs is 51 in number.

Table 15 Material quantity for the biobased construction interior wall Type 2.

Material	Volume (m^3)	Density (kg/m^3)	Quantity (kg)	EPD Program	Country of Origin
Wood stud	1.12	440	493	One Click LCA	Sweden
Hemp Insulation	8.36	35	293	One Click LCA	Sweden
CLT panel	3.72	481	1 787	One Click LCA	Sweden
FRP cladding	3.72	1 350	5 022	EPD Italy	Italy

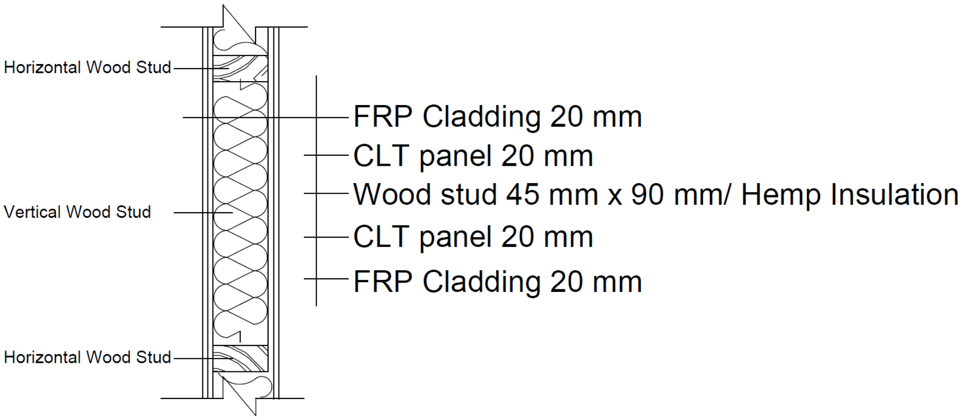

Figure 11 Wall section for the biobased construction interior wall Type 2 and 3.

4.9.13 Interior Wall for the Biobased Construction, Type 3

The sandwich wall panel used in the conventional construction is replaced with a biobased alternative. The wall build-up follows the same construction approach described in Section 4.9.12 Interior Wall for the Conventional Construction, Type 2, see Table 16. The main difference lies in the number of horizontal wood studs, which is adjusted to account for the height difference between the two walls. Consequently, this partition wall includes only three horizontal studs along its length: one at the bottom, one in the middle and one at the top.

Table 16 Material quantity for the biobased construction interior wall, Type 3.

Material	Volume (m^3)	Density (kg/m^3)	Quantity (kg)	EPD Program	Country of Origin
Wood stud	3.4	440	1 496	One Click LCA	Sweden
Hemp Insulation	27.3	35	956	One Click LCA	Sweden
CLT panel	12.1	481	5 820	One Click LCA	Sweden
FRP cladding	12.1	1 350	16 335	EPD Italy	Italy

4.9.14 Interior Wall for Both Constructions

This wall is the mesh wall that divides the egg laying chickens while allowing visibility for the employees. The length of the wall is 87 m while it has a height of 2.15 m, and a wire diameter is 0.0027 m. Using Normaclo (n.d.) steel fence system from BIMobject, the material quantity required has been extracted from Revit. While mapping this material quantity in the One Click LCA environment, generic EPD was not available. Hence, the EPD used was retrieved from a manufacturer, see Table 17.

Table 17 Material quantity for the interior mesh wall in both constructions.

Material	**Volume (m^3)**	**Density (kg/m^3)**	**Quantity (kg)**	**EPD Program**	**Country of Origin**
Mesh Wall	5.37	7 850	42 154.50	ZAG	Germany

4.9.15 Roof Truss for the Conventional Construction

The roof detail drawings of the conventional construction were not available at the time of this study; therefore, it was decided to proceed with having one steel truss and a biobased substitute, see Table 18 and Table 19. The calculation and assumptions are provided in Appendix A.4 Supporting Calculation for Section 4.9.15 Roof Truss

Table 18 Material quantity for the steel roof truss in the conventional construction.

Material	**Volume (m^3)**	**Density (kg/m^3)**	**Quantity (kg)**	**EPD Program**	**Country of Origin**
Steel truss	1.2	7 850	9 420	One Click LCA	Sweden

4.9.16 Roof Truss for the Biobased Construction

Relevant literature was reviewed to identify biobased alternatives for the roof truss system. The findings indicate that GLT beams can span up to 30 m, which corresponds to the span of the agricultural facility studied. The material quantity for the biobased alternative is provided in Table 19. The calculations and underlying assumptions are presented in Appendix A.5 Supporting Calculation for Section 4.9.16 Roof Truss

Table 19 Material quantity for the GLT truss in the biobased construction.

Material	**Volume (m^3)**	**Density (kg/m^3)**	**Quantity (kg)**	**EPD Program**	**Country of Origin**
GLT truss	558.7	475	265 382	One Click LCA	Sweden
Wood purlin	44.4	440	19 536	One Click LCA	Sweden

4.9.17 Ceiling for Both Constructions

In order to resist the high moisture load and harsh chemical environment, the FRP ceiling material is most suitable. The following quantity was calculated using an FRP ceiling thickness of 0.0015 mm and an area of 30 m x 110 m. While mapping this material quantity in the One Click LCA environment, generic EPD was not available; hence the EPD used is from a manufacturer, see Table 20.

Table 20 Material quantity for the ceiling in both constructions.

Material	Volume (m^3)	Density (kg/m^3)	Quantity (kg)	EPD Program	Country of Origin
FRP ceiling	6.6	1 350	6 682.5	EPD Italy	Italy

4.9.18 Roof Cover for Both Constructions

The roof cover is based on a Catnic Tata steel product available for download as a BIM model Bimobject.com. According to Tata steel (n.d.), the exterior cover consists of steel, which is suitable for the conventional construction. However, no biobased roof covering was available for the biobased alternative: therefore, a geo-based clay roof cover was selected as an alternative. In addition, the conventional construction uses XPS, while the biobased construction uses hemp wool insulation.

The purlins were calculated manually, as individual purlin elements were not included in the roof system 3D model. Each purlin measures 150 mm x 38 mm. The general roof build-up is similar for both construction types; however, the main differences lie in the choice of insulation and the top covering material. The conventional roof uses a corrugated steel sheet, whereas in the biobased alternative this replaced with a clay roof covering, see Table 21, 22, 23 and 24.

Table 21 Material quantity for the roof cover in the conventional construction (m^3).

Material	Volume (m^3)	Density (kg/m^3)	Quantity (kg)	EPD Program	Country of Origin
Catnic Steel Cover	14.9	7 850	116 965	One Click LCA	Sweden
Plywood	60.0	440	26 400	One Click LCA	Sweden
XPS insulation	332.7	23	7 652.10	One Click LCA	Sweden
Purlin	20.1	440	8 844.40	One Click LCA	Sweden
Plywood	40.0	440	17 600.00	One Click LCA	Sweden

Table 22 Material quantity for the roof cover in the biobased construction (m^3).

Material	Volume (m^3)	Density (kg/m^3)	Quantity (kg)	EPD Program	Country of Origin
Plywood	60.0	440	26 400.00	One Click LCA	Sweden
Hemp insulation	332.7	35	11 644.50	One Click LCA	Sweden
Purlin	20.1	440	8 844.40	One Click LCA	Sweden
Plywood	40.0	440	17 600.00	One Click LCA	Sweden

Table 23 Material quantity for the roof cover in both constructions (m^2).

Material	Area (m^2)	Density (kg/m^2)	Quantity (kg)	EPD Program	Country of Origin
Vapor barrier	6 652	0.20	1 330.40	OKOBAUDAT	Sweden

Table 24 Material quantity for the roof cover in the biobased construction (m^2).

Material	**Area (m^2)**	**Density (kg/m^2)**	**Quantity (kg)**	**EPD Program**	**Country of Origin**
Clay Roof tile	6 652	35	232 820	OKOBAUDAT	Sweden

4.9.19 Door for Both Constructions

Details regarding the sizes and number of doors can be found in Appendix 1, section A.6. The door used has aluminum cladding with wooden frame, see Table 25.

Table 25 Total door area for both constructions.

Material	**Area (m^2)**	**Density (kg/m^2)**	**Quantity (pcs)**	**EPD Program**	**Country of Origin**
Door	22.94	35	8	One Click LCA	Sweden

4.9.20 Window for Both Constructions

The window size and quantity along with the dimension are provided in Appendix 1 A.7 Supporting Calculation for Section 4.9.20 Window for Both Constructions. The window used has aluminum cladding with wooden frame, see Table 26.

Table 26 Total window area for both constructions.

Material	**Area (m^2)**	**Density (kg/m^2)**	**Quantity (pcs)**	**EPD Program**	**Country of Origin**
Door	22.94	35	36	One Click LCA	Sweden

5 Results

5.1 Environmental Impacts by Life Cycle Stages

The results of the environmental impacts by life cycle stages are presented in Figure 12. For both construction types, stages A1-A3 exhibit the highest contributions across all impact categories. Stage A4 is a significant contributor to ADPF in both scenarios, while stage A5 shows a noticeably higher impact in the biobased construction compared with the conventional one.

In the conventional construction, stages B4-B5 show relatively low impacts across categories. In contrast, the biobased construction records higher contributions in these stages, particularly in ADPF, GWP-biogenic, GWP-total. For stage C2, the biobased construction demonstrates a higher environmental impact in ADPF, whereas the conventional construction shows comparatively lower values.

Regarding stage D, the conventional construction performs better, demonstrating larger beneficial values in ADPF, with ADPF displaying the strongest avoided burden effect.

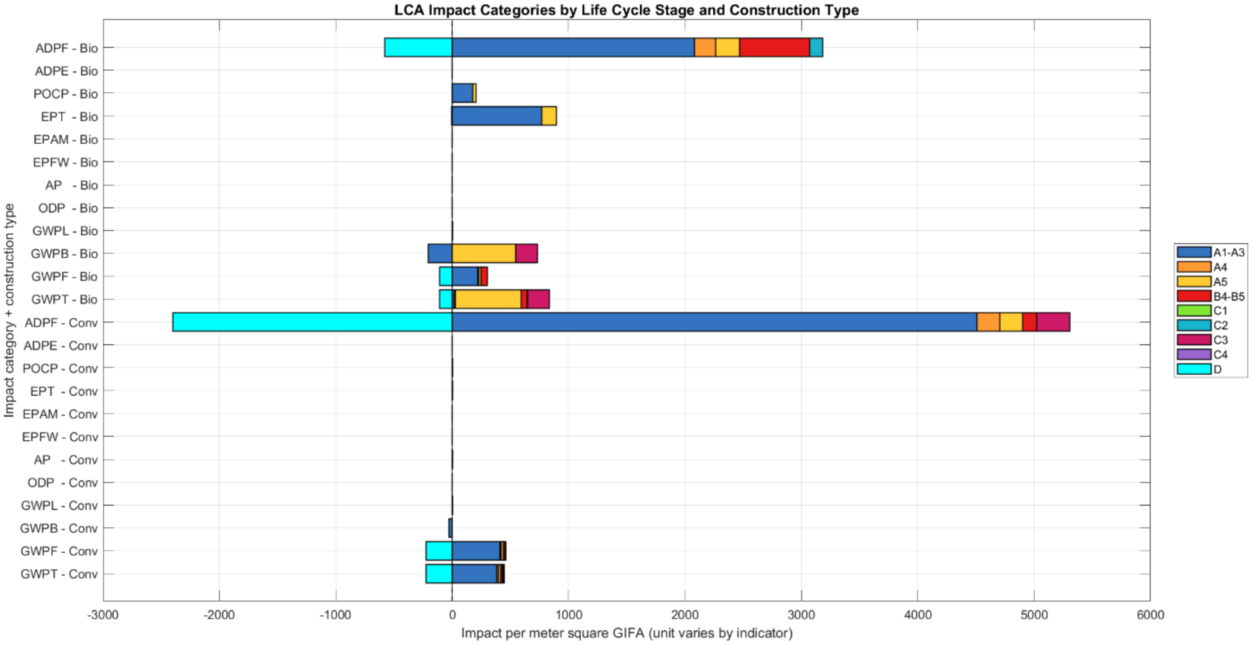

Figure 12 Environmental impact by life cycle stages for both constructions.

5.2 GWP by Life Cycle Stages

The results of the GWP-total by life cycle stages are presented in Figure 13. For the biobased construction GWP-total in stage A1-A3 is 16 kg CO_2-eq/m^2 GIFA for biobased construction whereas the conventional construction is at a higher value of 383 kg CO_2-eq/m^2 GIFA. The transportation stage A4 contributes a minor share in both constructions. The installation stage A5 in the biobased alternative exhibits higher GWP-total 563 kg CO_2-eq/m^2 GIFA than the conventional construction 17 kg CO_2-eq/m^2 GIFA.

Replacement and refurbishment stage B4-B5 for the biobased construction has an impact of 54 kg CO_2-eq/m^2 GIFA whereas the conventional construction has an impact of 12 kg CO_2-eq/m^2 GIFA. End of life transport C2 has a relatively small contribution in both constructions, the conventional construction having 9 kg CO_2-eq/m^2 GIFA and the biobased construction having 3 kg CO_2-eq/m^2 GIFA. The benefits and load beyond the system boundary stage D for the conventional construction has GWP-total of -224 kg CO_2-eq/m^2 GIFA whereas the biobased construction has -106 kg CO_2-eq/m^2 GIFA.

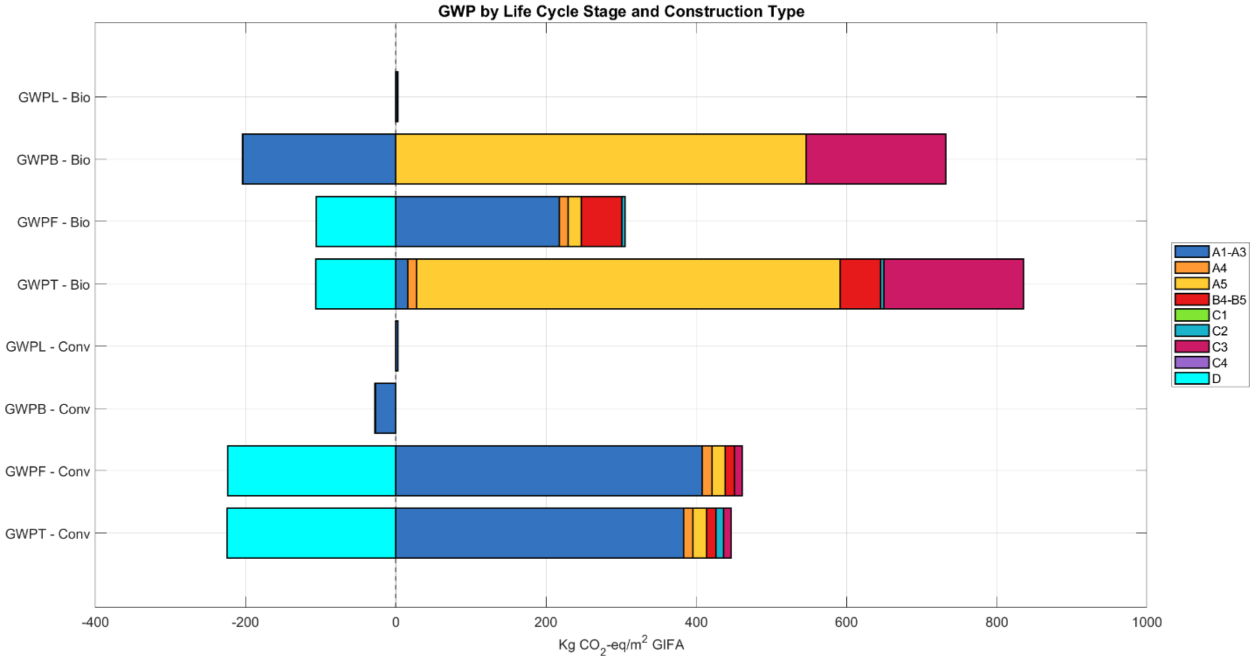

Figure 13 GWP for the both construction.

5.3 Environmental Impact by Materials

The results of the environmental impacts by materials are presented in Figure 14. In the conventional construction, the highest impacts are observed in Abiotic Depletion Potential Fossil (ADPF), with the greatest contributions coming from steel sheets and concrete, followed by FRP, hollow steel sections (HSS) and plywood. In contrast, the biobased construction shows notable contributions from GLT, FRP and concrete across multiple impact categories, with GLT exhibiting particularly high values, especially in ADPF.

Overall, ADPF consistently presents the largest magnitude of impact across the dataset. This is primarily driven by steel-based materials in the conventional construction and by GLT/plywood products in the biobased construction.

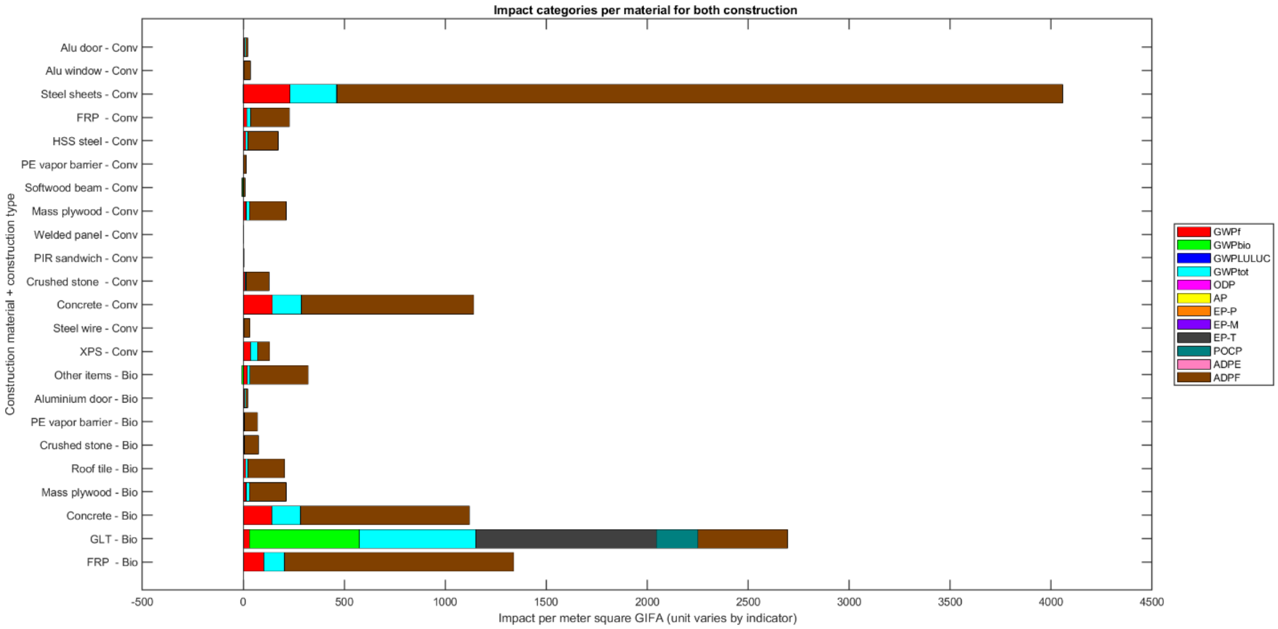

Figure 14 Environmental impact categories by material for both constructions.

5.4 GWP-total by Material

The results of the GWP-total by materials are presented in Figure 15. In the biobased construction GLT is the dominant contributor, followed by concrete and FRP, while insulation materials, roofing tiles, and the other components contribute only marginally, in the conventional construction, the largest impacts originate from steel sheets, concrete and XPS, with the remaining materials contributing moderately.

Overall, the figure shows that the single largest contributor in the biobased design is GLT, whereas in the conventional construction it is steel sheet cladding. Both materials exhibit comparable magnitudes of impact but on opposite sides of the chart. The biobased construction is characterized by fewer materials with very high GWP values, while the conventional construction displays a broader spread of medium to high impact materials.

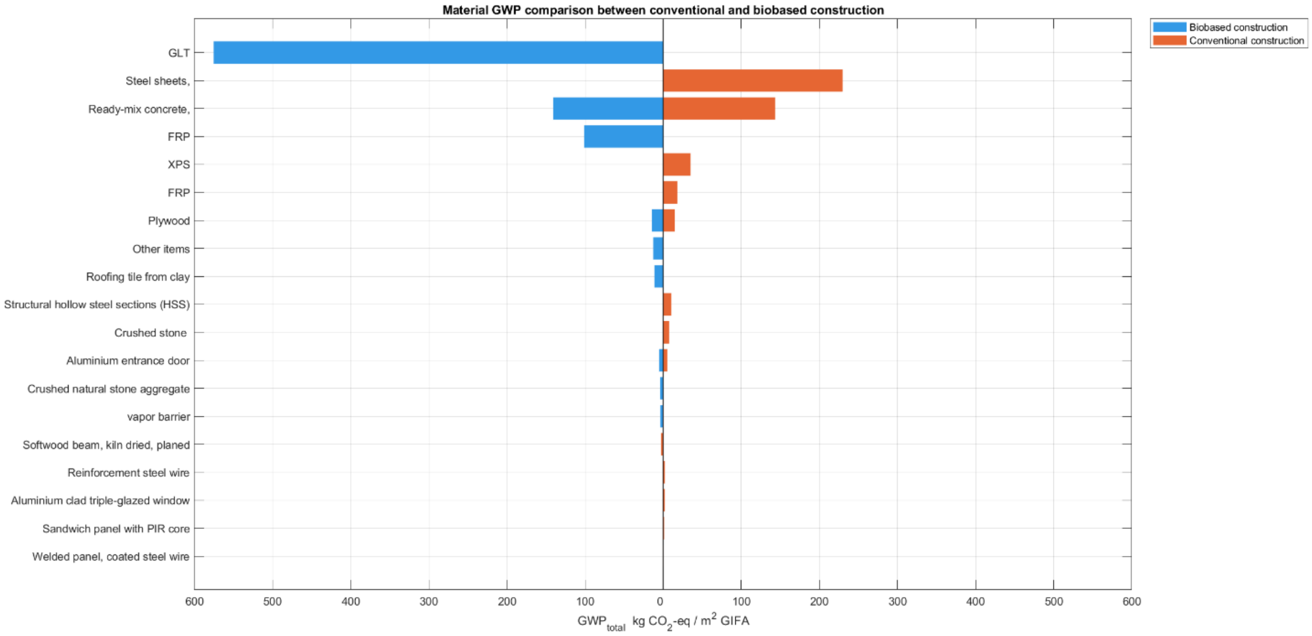

Figure 15 Material GWP comparison

5.5 One Click LCA Carbon Benchmark

The results of One Click LCA carbon benchmark are presented in Figure 16. One Click LCA allows the user to evaluate the climate impact of the building among validated similar buildings in its database. Based on Nordic Industrial buildings 2025 among a sample of 38 validated buildings in One Click LCA database, the conventional construction is benchmarked at E with a carbon impact of 462 kg CO_2-eq/m^2 whereas the biobased construction is benchmarked at 307 kg CO_2-eq/m^2.

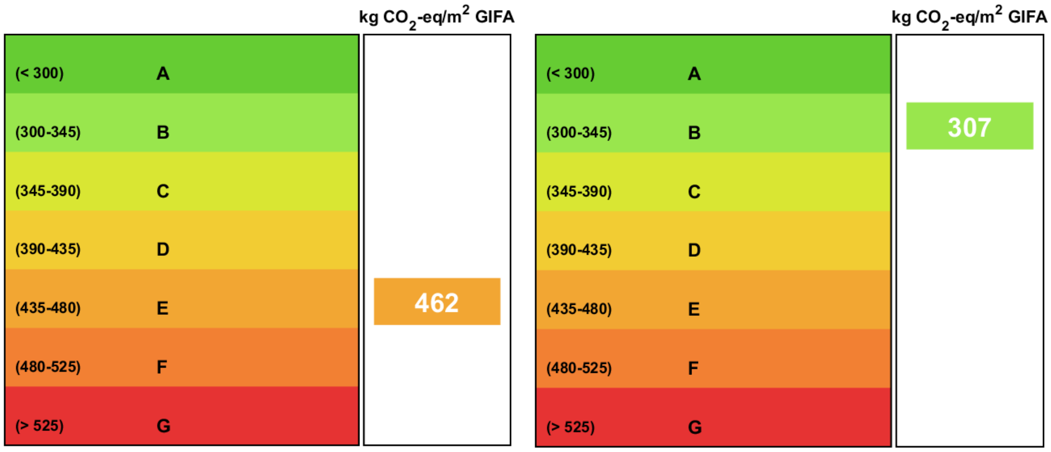

Figure 16 One click LCA carbon benchmark cradle to grave (A1-A4, B4-B5, C1-C4)

6 Discussion

6.1 Environmental Impacts by Life Cycle Stages

The biobased construction performs better in stage A1-A3 for ADPF, primarily because its production relies far less on fossil-based resources. In contrast, the conventional construction receives a substantially larger benefit in stage D, where the recycling of steel generates significantly avoided burdens, particularly in terms of fossil resource depletion.

6.2 GWP by Life Cycle Stages

In the product stage A1-A3, by shifting from conventional construction to biobased construction it was possible to achieve a carbon impact reduction of 367 kg CO_2-eq/m^2 GIFA i.e. 95 % decrease in GWP-total. This indicates that the manufacturing of steel, concrete and XPS are carbon intensive compared to the biobased timber products and hemp wool. Similarly, for this stage GWP-biogenic in the biobased construction has a carbon sequestration potential of -176 kg CO_2-eq/m^2 GIFA i.e. the shift from conventional to biobased construction has a potential of sequestering carbon 86 % higher.

The increase in GWP or the biobased construction in stage A5 is due to material wastage during installation making it the single largest contributing stage to GWP. This indicates that this stage needs further attention and better installation techniques needs to be devised in order to minimize material waste.

The increase in carbon impact in the replacement and refurbishment stage B4-B5 for the biobased construction reflects the assumption that biobased components require periodic replacement within the fifty-year analysis period. Whereas in the conventional construction it indicates that it lasts for the full analysis period and requires less frequent refurbishment.

The slight peak in waste processing transportation stage C2 for the conventional construction with a value of 5 kg CO_2-eq/m^2 GIFA indicates a larger mass being transported. The waste disposal C3 stage for conventional construction is 9 kg CO_2-eq/m^2 GIFA whereas for the biobased construction it has a higher value of 185 kg CO_2-eq/m^2 GIFA. This indicates the release of biogenic carbon that had already been sequestered due to waste disposal techniques such as incineration or biological decay. The waste disposal C4 for both constructions shows minimal contribution. The benefits and load beyond the system boundary stage D shows a benefit twice that of the biobased construction. This is due to the recyclability of steel which generates substantial substitution benefit by displacing primary material production.

6.3 Environmental Impact by Materials

The results highlight notable differences in environmental impacts across material groups and emphasize the strong influence of fossil-based materials on overall impact levels. The conventional construction shows particularly high ADPF consumption, most prominently for steel sheets, reflecting a substantial dependence on fossil-derived energy during raw material extraction, manufacturing and processing. This observation is consistent with the broader literature, which identifies steel production as both energy-intensive and emission-intensive.

In contrast, the biobased construction displays a more distributed impact profile, with no single material approaching the magnitude observed for steel sheets. Nonetheless, important biobased substitutes such as GLT still exhibit considerable impacts especially in GWP-total and POCP indicating that the biobased option is not universally low-impact across all categories. This suggests that although renewable materials reduce fossil depletion and may offer advantages such as biogenic carbon sequestration, their production process and the larger material volumes typically required can offset these benefits in certain impact indicators.

6.4 GWP-total by Materials

In the biobased construction, GLT records the highest GWP-total, but this is largely driven by material wastage during the installation stage A5 rather than by fossil carbon emissions from its production. In contrast, the conventional construction relies on materials such as steel sheets and concrete, which are intrinsically fossil-intensive and require substantial energy inputs during manufacturing.

The findings highlight that stage A5 needs further investigation, as it is responsible for a significant share of the cumulative increase in GWP-total for the biobased scenario. Furthermore, the FRP component shows a markedly higher impact in the biobased construction. This difference stems from the greater quantity of FRP incorporated into the biobased design, where it is used both as interior wall cladding to protect moisture sensitive wood materials and as ceiling materials. In comparison, the conventional construction applies to FRP only in the ceiling, resulting in a substantially lower overall construction.

6.5 One Click LCA Carbon Hero Benchmark

According to Sweden Green Building Council (SGBC, 2025) buildings categorized as other buildings and who achieve between 370 kg CO_2-eq/m^2 – 330 kg CO_2-eq/m^2 of heated floor area (HFA) are awarded silver, in addition those buildings that have achieved – 330 kg CO_2-eq/m^2 of HFA are awarded gold. Based on these criteria and assuming the GIFA is the HFA, the biobased construction is qualified to earn a gold certificate.

The motivation of this study was the fact that these buildings are one of the exempted buildings by Boverket as well as lack of sufficient comparative LCA done in animal shelter. The fact that these buildings are exempted from climate declaration overlooks this problem. Hence such studies can be an eye opener for policy makers in to investigating this area more thoroughly.

7 Conclusion

This comparative LCA evaluates the environmental impacts of conventional and biobased construction for a poultry facility in Borby, Sweden. The results show that material choice and life cycle stage greatly influence total impacts, with each construction method presenting distinct advantages and trade-offs.

In stage A1-A3 the biobased construction performs better. Replacing carbon intensive materials such as steel, concrete and XPS with timber products and hemp insulation results in a 95% reduction in GWP-total and significantly higher biogenic carbon sequestration, demonstrating the strong mitigation potential of renewable materials.

However, the biobased option does not outperform the conventional one across all stages. Stage A5, is the largest single contributor to GWP-total for the biobased case, mainly due to high GLT wastage, partially offsetting earlier gains. This highlights the need for improved construction planning and waste reduction strategies.

During stage B4-B5, the biobased design shows higher impacts because several components require periodic maintenance within the 50-year period, whereas the conventional construction benefits from longer lasting materials. At the end of life, the conventional construction achieves larger benefits in stage D due to steel's high recyclability, resulting in greater avoided burdens, especially for ADPF and GWP-total.

Material level analysis further reinforces these differences, GLT dominates impacts in the biobased case primarily due to installation losses, while steel sheets are the main drivers of fossil resource depletion and GWP in the conventional case. This confirms that biobased materials reduce fossil dependency but still require full life cycle evaluation.

Benchmarking with One Click LCA's Carbon Hero tool shows an overall advantage for the biobased design, which reaches 307 kg CO_2-eq/m^2 GIFA, outperforming the conventional construction 462 kg CO_2-eq/m^2 GIFA and meeting the SGBC Gold threshold. This is notable given that agricultural buildings are exempt from climate declarations, revealing a current regulatory gap.

Overall, the study demonstrates that shifting from conventional to biobased construction can significantly reduce embodied carbon, particularly in manufacturing stages, and provides guidance for low carbon strategies in agricultural building design.

The study also has limitations, relevant EPDs were difficult to identify and inconsistencies were found, for example duplicate Benders EPDs withing the same ID (EPD HUB-1678) but different environmental summaries. Such inconsistencies highlight the need for stricter standardization and better database maintenance. In addition, structural quantities were estimated using literature due to missing roof drawings, and no structural engineering verification performed, meaning some materials may be under or overestimated.

The study focuses solely on embodied carbon, without assessing operational carbon associated with heating, ventilation, lighting, and equipment use during the building lifetime. As a result, the analysis does not capture the full climate impact of the facility. Finally, only GLT was assessed as the main timber system, alternative timber products such as LVL or DLT may offer lower impacts and should be explored in future research.

Declaration of Generative AI Use

I have used Chat GPT for improving the English text and rephrasing the English texts that I have written and creating the citation under reference section. I have also used it to create a MATLAB code to plot the graphs shown in the result section. Furthermore, I have used Microsoft translation service to translate the text "Ændret materialevalg kan reducere Konceptstaldens klimaaftryk" from Danish to English.

I Declare that I have not used any form of Generative AI for data generation, analysis or interpretation.

Hundaol Dega

Reference

Aguilar-Santana, J. L., Velasco-Carrasco, M., & Riffat, S. (2020). Thermal transmittance (U-value) evaluation of innovative window technologies. *Future Cities and Environment, 6*(1), 12, 1–13. Accessible via the link accessed March 17, 2025, https://doi.org/10.5334/fce.99

Alam, Muhiuddin. n.d. "SteelSolver.com – Precision Tools. Powerful Solutions." SteelSolver.com. Accessed August 17, 2025. https://www.steelsolver.com/.

American Institute of Architects. (2010). *AIA Guide to Building Life Cycle Assessment in Practice*. The American Institute of Architects. Accessible via the link accessed on May 06, 2025 https://content.aia.org/sites/default/files/2016-04/Building-Life-Cycle-Assessment-Guide.pdf

Balasbaneh, A. T., & Sher, W. (2024). A systematic literature review of life cycle sustainability assessment of mass timber in the construction industry toward circular economy. *Environment, Development and Sustainability. Accessible via the link accessed on January 29 2025* https://doi.org/10.1007/s10668-024-05377-9

Balasbaneh, A. T., Marsono, A. K. B., & Khaleghi, S. J. (2018). Sustainability choice of different hybrid timber structure for low medium cost single-story residential building: Environmental, economic and social assessment. *Journal of Building Engineering, 20,* 235–247 accessible via the link accessed on February 12, 2025, https://doi.org/10.1016/j.jobe.2018.07.006

Balasbaneh, A. T., & Sher, W. (2021). Comparative sustainability evaluation of two engineered wood-based construction materials: Life cycle analysis of CLT versus GLT. *Building and Environment, 204,* 108112. Accessible via the link accessed on September 03, 2025, https://doi.org/10.1016/j.buildenv.2021.108112

Bida, S. M., Abdul Aziz, F. N. A., Jaafar, M. S., Hejazi, F., & Abu Bakar, N. (2021). Thermal resistance of insulated precast concrete sandwich panels. *International Journal of Concrete Structures and Materials, 15*(1), 41.Accessible via the link accessed on April 22 2025 https://doi.org/10.1186/s40069-021-00477-6

Biofib. (n.d.). *Biofib' chanvre*. BIMobject. Accessible via the link accessed on June 01, 2025, from https://www.bimobject.com/en/biofib/product/biofib-chanvre

Bansal, R., Barshilia, H. C., & Pandey, K. K. (2024). *Nanotechnology in wood science: Innovations and applications*. International Journal of Biological Macromolecules, 262, 130025. Accessible via the link, accessed on Dec 26, 2025 https://doi.org/10.1016/j.ijbiomac.2024.130025

Bourbia, S., Kazeoui, H., & Belarbi, R. (2023). A review on recent research on biobased building materials and their applications. *Materials for Renewable and Sustainable Energy*. Accessible via the link accessed on February 13, 2025, https://doi.org/10.1007/s40243-023-00234-7

Boverket. (2022). *Climate declarations – what applies?* Swedish National Board of Housing, Building and Planning. Accessible via the link accessed on June 01 2025 https://www.boverket.se/en/start/building-in-sweden/developer/rules-for-building/climate-declaration/

Campbell, E., Keeffe, G., Cullen, S., Richmond, A., Beagan, S., Lavery, U., McKenna, B., & Lester, S. (2023). *Research-by-design in complex systems: Reflections on approaches used to reimagine environmentally sustainable, high-welfare poultry housing futures*. Sustainability, 15(7), 5808. Accessible via the link accessed on Jan 03 2026. https://doi.org/10.3390/su15075808

Chen, C. X., Pierobon, F., & Ganguly, I. (2019). Life cycle assessment (LCA) of cross-laminated timber (CLT) produced in western Washington: The role of logistics and wood species mix. *Sustainability, 11*(5), 1278. Accessible via the link accessed on February 13, 2025, https://doi.org/10.3390/su11051278

Citadel Architectural Products. (n.d.). *NST9989*. BIMobject. Accessible via the link accessed on August 07, 2025, https://www.bimobject.com/en/citadelarchitectural/product/nst9989

De Belie, N., Richardson, M., Braam, C. R., Svennerstedt, B., Lenehan, J. J., & Sonck, B. (2000). *Durability of building materials and components in the agricultural environment: Part I, The agricultural environment and timber structures*. Journal of Agricultural Engineering Research, 75(3), 225–241. Accessible via the link accessed on February 04, 2025, https://doi.org/10.1006/jaer.1999.0505

Decontamination Institute. (2024). *General information about CCA (chromated copper arsenate)*. Accessible via the link accessed on December 26, 2025 https://www.decontaminationinstitute.org/information/hazardous-substances/contaminated-wood/general-information-about-cca-chromated-copper-arsenate

Djakfar, L., Nur, A., Rahman, A., Abdullah, R. S., & Haron, Z. (2021). *Sustainable construction of precast concrete structure using green technology: A review*. Sustainability, 13(22), 12509. Accessible via the link accessed on June 02, 2025, https://doi.org/10.3390/su132212509

Duan, Z., Huang, Q., Sun, Q., & Zhang, Q. (2022). Comparative life cycle assessment of a reinforced concrete residential building with equivalent cross laminated timber alternatives in China. *Journal of Building Engineering, 62,* 105357.Accessible via the link accessed on August 29, 2025 https://doi.org/10.1016/j.jobe.2022.105357

Duan, Z. (2023). Impact of climate change on the life cycle greenhouse gas emissions of cross-laminated timber and reinforced concrete buildings in China. *Journal of Cleaner Production, 395,* 136446. Accessible via the link accessed on August 29, 2025 https://doi.org/10.1016/j.jclepro.2023.136446

Ejechi, B. O., & Akpomedaye, D. E. (1998). The hurdle effect of ureolytic *Proteus* sp. activity and *Trichoderma viride* culture filtrate on growth and wood deteriorating activities of four fungi. *International Biodeterioration & Biodegradation, 41*(3–4), 153–155. Acessible via the link accessed on August 29 2025 https://doi.org/10.1016/S0964-8305(97)00083-8

European Committee for Standardization. (2011). *Sustainability of construction works—Assessment of environmental performance of buildings—Calculation method* (SS-EN 15978:2011). Swedish Standards Institute (SIS). Accessed February 04, 2025.

European Committee for Standardization. (2019). *Sustainability of construction works—Environmental product declarations—Core rules for the product category of construction products* (SS-EN 15804:2012+A2:2019). Swedish Institute for Standards (SIS). Accessed February 04, 2025.

Food and Agriculture Organization of the United Nations. (1986). *Wood preservative manual* (FAO Forestry Paper No. 76). Food and Agriculture Organization of the United Nations. Accessible via the link accessed on February 04, 2025, https://www.fao.org/3/t0235e/t0235e00.htm

Fossum, O., Jansson, D. S., Etterlin, P. E., & Vågsholm, I. (2009). Causes of mortality in laying hens in different housing systems in 2001 to 2004. *Acta Veterinaria Scandinavica, 51*(3). Accessible via the link accessed on February 04, 2025, https://doi.org/10.1186/1751-0147-51-3

Gayake, P. R., Mehetre, S. M., Dhawale, S., Hande, P., Lohote, N., & Maskare, R. (2020). *A review paper on internal thermal insulation for masonry wall in historic multifamily building*. International Research Journal of Engineering and Technology (IRJET), 7(4), 3726–3732. Accessible via the link accessed on May 11, 2025, IRJET-V7I4725.pdf

Greene, J. M., Hosanna, H. R., Willson, B., & Quinn, J. C. (2023). Whole life embodied emissions and net-zero emissions potential for a mid-rise office building constructed with mass timber. *Sustainable Materials and Technologies, 35,* e00528. https://doi.org/10.1016/j.susmat.2022.e00528

Guo, H., Liu, Y., Meng, Y., Huang, H., Sun, C., & Shao, Y. (2017). A comparison of the energy saving and carbon reduction performance between reinforced concrete and cross-laminated timber structures in residential buildings in the severe cold region of China. *Sustainability, 9*(8), 1426. Accessible via the link, accessed on September 01, 2025, https://doi.org/10.3390/su9081426

Head, M., Magnan, M., Kurz, W. A., Levasseur, A., Beauregard, R., & Margni, M. (2021). Temporally differentiated biogenic carbon accounting of wood building product life cycles. *SN Applied Sciences, 3*(62).Accessible via the link accessed on September 01, 2025, https://doi.org/10.1007/s42452-020-03979-2

Hassan, O. A. B., Emad, N. A. A., & Abdulahad, G. (2022). A comparative study between glulam and concrete columns in view of design, economy and environment. *Case Studies in Construction Materials, 16*, e00966. Accessible via the link accessed on June 03, 2025, https://doi.org/10.1016/j.cscm.2022.e00966

International Organization for Standardization. (2019). *Sustainability of construction works—Environmental product declarations—Core rules for the product category of construction products* (SS-EN 15804:2012+A2:2019). Swedish Standards Institute (SIS) Accessed Feb 04, 2025.

Jang, H.-J., Ahn, Y.-H., & Tae, S.-H. (2022). *Proposal of major environmental impact categories of construction materials based on life cycle impact assessments*. Materials, 15(14), 5047. Acessible via the link accessed on May 06, 2025, https://doi.org/10.3390/ma15145047

Jayalath, A., Navaratnam, S., Ngo, T., Mendis, P., Hewson, N., & Aye, L. (2020). Life cycle performance of Cross Laminated Timber mid-rise residential buildings in Australia. *Energy and Buildings, 223,* 110091. Accessible via the link accessed on September 03, 2025, https://doi.org/10.1016/j.enbuild.2020.110091

Joseph, J. D. R., Prabakar, J., & Alagusundaramoorthy, P. (2019). Experimental study on the flexural behavior of insulated concrete sandwich panels with wires as shear connectors. *Alexandria Engineering Journal, 58*(3), 901–908. Acessible via the link accessed on May 10, 2025, https://doi.org/10.1016/j.aej.2019.08.005

Kinnane, O., West, R., & Hegarty, R. O. (2020). Structural shear performance of insulated precast concrete sandwich panels with steel plate connectors. *Engineering Structures, 215*, Article 110691. Acessible via the link accessed on May 10, 2025, https://doi.org/10.1016/j.engstruct.2020.110691

Kitek Kuzman, M., Oblak, L., & Vratuša, S. (2010). Glued laminated timber in architecture. *Drvna Industrija, 61*(3), 197–204. Accessible via the link accessed on January 29, 2025, https://doi.org/10.5552/drind.2010.1014

Koesling, M., Ruge, G., Fystro, G., Torp, T., & Hansen, S. (2015). *Embodied and operational energy in buildings on 20 Norwegian dairy farms – Introducing the building construction approach to agriculture*. Energy and Buildings, 108, 330–345. https://doi.org/10.1016/j.enbuild.2015.09.012

Larivière-Lajoie, R., Blanchet, P., & Amor, B. (2022). Evaluating the importance of the embodied impacts of wall assemblies in the context of a low environmental impact energy mix. *Building and Environment, 207,* 108534. Accessible via the link accessed on September 01, 2025 https://doi.org/10.1016/j.buildenv.2021.108534

Lindab. (n.d.). *Sandwich Panel BASE – Horizontal installation*. BIMobject. Accessible via the link accessed on August 09 2025 https://www.bimobject.com/en/lindab/product/p-panel-base-h

Lolli, N., Fufa, S. M., & Wiik, M. K. (2019). An assessment of greenhouse gas emissions from CLT and glulam in two residential nearly zero energy buildings. *Wood Material Science & Engineering, 15*(6), 1–14. Accessible via the link accessed on February 18, 2025 https://doi.org/10.1080/17480272.2019.1655792

Machado, N. B., D'Amico, B., De Santis, I., & Bohne, R. A. (2025). *Embodied GHG emissions of reinforced concrete and timber structures: Relevance, driving factors and target values*. Building and Environment, 275, 112759.Accessible via the link accessed on https://doi.org/10.1016/j.buildenv.2025.112759

One Click LCA Academy. (n.d.-a). *2. Life cycle assessment – What is it?* [Video]. One Click LCA Academy. Accessed on April 22, 2025, from https://academy.oneclicklca.com/courses/take/introduction-to-embodied-carbon-lca-and-sustainable-construction/lessons/54249709-2-life-cycle-assessment-what-is-it

One Click LCA Academy. (n.d.-b). *Life Cycle Assessment: Why is it important?* Accessed on April 26, 2025, from https://academy.oneclicklca.com/courses/take/introduction-to-embodied-carbon-lca-and-sustainable-construction/lessons/54249714-3-life-cycle-assessment-why-is-it-important

One Click LCA Academy. (n.d.-c). *4. Standards guiding LCA* [Video]. One Click LCA Academy. Accessed on April 21, 2025, from https://academy.oneclicklca.com/courses/take/introduction-to-embodied-carbon-lca-and-sustainable-construction/lessons/54249719-4-standards-guiding-lca

One Click LCA Academy. (n.d.-d). *What is BIM and why integrate LCA with it?* Accessed on April 27, 2025, from https://academy.oneclicklca.com/courses/take/one-click-lca-integration-for-revit/texts/49585271-1-2-what-is-bim-and-why-integrate-lca-with-it

Petersen, A. K., & Solberg, B. (2002). Greenhouse gas emissions, life-cycle inventory and cost-efficiency of using laminated wood instead of steel construction: Case beams at Gardermoen airport. *Environmental Science & Policy, 5*(2), 169–182. Accessible via the link accessed on January 22, 2025, https://doi.org/10.1016/S1462-9011(01)00044-2

Petersen, A. K., & Solberg, B. (2005). *Environmental and economic impacts of substitution between wood products and alternative materials: A review of micro-level analyses from Norway and Sweden*. Forest Policy and Economics, 7(3), 249–259. Accessible via the link accessed on January 22, 2025, https://doi.org/10.1016/S1389-9341(03)00063-7

Petrovic, B., Eriksson, O., & Zhang, X. (2023). Carbon assessment of a wooden single-family building – A novel deep green design and elaborating on assessment parameters. *Building and Environment, 233,* 110093. Accessible via the link accessed on September 03, 2025, https://doi.org/10.1016/j.buildenv.2023.110093

Piccardo, C., & Gustavsson, L. (2021). *Implications of different modelling choices in primary energy and carbon emission analysis of buildings*. *Energy and Buildings, 247*, Article 111145. Accessible via the link accessed on January 29, 2025, https://doi.org/10.1016/j.enbuild.2021.111145

Pierobon, F., Huang, M., Simonen, K., & Ganguly, I. (2019). Environmental benefits of using hybrid CLT structure in midrise non-residential construction: An LCA based comparative case study in the U.S. Pacific Northwest. *Journal of Building Engineering, 26,* 100862. Accessible via the link accessed on February 21, 2025, https://doi.org/10.1016/j.jobe.2019.100862

Poulsen, K. (2024). *Ændret materialevalg kan reducere Konceptstaldens klimaaftryk* (Meddelelse Nr. 1279). SEGES Innovation P/S. accessible via the link accessed on January 22, 2025, https://svineproduktion.dk/-/media/PDF/I-stalden/Staldindretning/Slagtesvinestald/Konceptstald/Konceptstalden_fulde_dokument.ashx

Ramage, M. H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D. U., … Scherman, O. (2017). The wood from the trees: The use of timber in construction. *Renewable and Sustainable Energy Reviews, 68,* 333–359. Accessible via the link accessed on February 02, 2025, https://doi.org/10.1016/j.rser.2016.09.107

Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. Energy and Buildings, 42(10), 1592-1600. Accessible via the link accessed on December 23 2025, https://doi.org/10.1016/j.enbuild.2010.05.007

Richardson, B. A. (2002). *Wood Preservation: Second Edition*. E & FN SPON, London. Accessible via the link accessed on September 02, 2025, Wood Preservation

Simón-Portela, M., Villar-García, J. R., Rodríguez-Robles, D., & Vidal-López, P. (2023). *Optimization of glulam regular double-tapered beams for agroforestry constructions*. Applied Sciences, 13(9), 5731. Accessible via the link accessed on May 12, 2025, https://doi.org/10.3390/app13095731

Sweden Green Building Council. (2025). *Miljöbyggnad 4.1: Manual nybyggnad*. Sweden Green Building Council. Accessible via the link accessed on April 07, 2025 https://www.sgbc.se/app/uploads/2025/04/250306_MB_Nybyggnad4.1.pdf

Swedish Chemicals Agency (KemI). (2024). *Wood protection with creosote*. Accessible via the link accessed on January Dec 26, 2025 https://www.kemi.se/lagar-och-regler/lagstiftningar-inom-kemikalieomradet/bekampningsmedel/biocider/vanliga-typer-av-biocidprodukter/traskyddsmedel/traskydd-med-kreosot

Swedish Wood. 2022. *Design of Timber Structures – Volume 3: Examples*. 3rd ed. Stockholm: Swedish Wood. Accessible via the link accessed on June 03, 2025. https://www.swedishwood.com/siteassets/5-publikationer/pdfer/sw-design-of-timber-structures-vol3-2022.pdf

Tata Steel. (n.d.). *Catnic Urban Warm Roof* [Product page]. BIMobject. https://www.bimobject.com/en/tata-steel/product/catnic-urban-warm-roof

Udas, H. (2025, February 3). *EN 15804+A2: What the changes mean for EPDs*. One Click LCA. Accessible via the link accessed on April 22, 2025, https://oneclicklca.com/en/resources/articles/en-15804-changes-epds

Yuan, X., Moreu, F., & Hojati, M. (2022). Cost-effective inspection of rebar spacing and clearance using RGB-D sensors. *Sensors, 22*(5), 1865. Accessible via the link accessed on June 02 2025 https://doi.org/10.3390/s22051865

Zaki, M. F. M., Zahid, M. Z. A. M., Ayob, A., & Fang, T. C. (2014). *Calculation of axial loads on columns by tributary area method and finite element method*. Applied Mechanics and Materials, 695, 576–579. Accessible via the link accessed on June 03, 2025, https://doi.org/10.4028/www.scientific.net/AMM.695.576

Zabalza Bribián, I., Valero Capilla, A., & Aranda Usón, A. (2011). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Building and Environment, 46*(5), 1133–1140.Accessible via the link Accessed on January 25, 2025, https://doi.org/10.1016/j.buildenv.2010.12.002

Appendix A Detailed Calculation

A.1 Supporting Calculation for Section 4.7.2 Exterior wall Biobased

First, the size of the GLT column is determined and proceed to the biobased external wall. In assuming the size of the GLT column wind load, beam self-weight, roof dead load and snow load for an industrial hall spanning 36 m from Swedish Wood (2022) has been referred. The poultry building of this thesis has a span of 30 m, hence these loads are assumed to be reasonable to determine the GLT size. The respective value of each load type is summarized in Table 27.

Table 27 Assumption of uniformly distributed load to determine the size of GLT column kN/m^2 as cited in Swedish Wood (2022)

Wind Load	Beam Self Weight	Roof Dead Load	Snow Load
0.61	0.6	0.6	1.5
Total Roof Load		3.3	

Hassan et al. (2022) conducted a comparative study between GLT and concrete columns regarding design, economy and environment. In which the GLT column is spaced 6 m apart center to center. There are 3 sets of options in height and axial force acting on the GLT column. This brings it to a total of nine GLT column sizes. The available options for heights are 3 m, 4 m and 5 m. The options regarding axial load are 100 kN, 500 kN and 1 000 kN.

In order to make a better assumption and choose the size of the GLT column which neither overlooks material quantity nor undermines the structural integrity of the building, the tributary area method discussed in Zaki et al. (2014) has been used.

$$Tributary\ area\ (m^2)\ \times\ Total\ roof\ load\ (kN/m^2)\ =\ Axial\ load\ on\ column\ (kN) \tag{1}$$

The tributary area is the area measured from center to center from one column to the other. The GLT being capable of having a 6 m span in each direction, this gives a tributary area of 36 m^2.

Substituting the total roof load and the tributary area in equation (1) is as follows:

$$36\ (m^2)\ \times\ 3.31\ (kN/m^2)\ =\ 119.16\ (kN)$$

This gives an axial load of 119.16 kN that one column can bear. Based on this calculation and the height of the poultry building two types of GLT size have been assumed. According to Hassan et al. (2022) GLT with a height of 3 m and 500 kN has a dimension of 115 mm x180 mm. This will be used for the employee section since the height required is 2.7 m high, the total number of GLT columns in this section is 30. Furthermore, GLT with a height of 4 m and 500 kN has a dimension of 215 mm x 270 mm. This will be used in the section where the chickens are housed which requires a height of 3.2 m, the total number of GLT column in this section is 96.

The arrangement of GLT as a structural column is illustrated in Figure 17. In order to avoid being misguided the reader should note that the illustration is prepared as a means of visual aid and not as an official architectural document. The measurements on the drawing are in meters. The drawing is prepared on a scale of 1:1. Based on the sizes and the spacing mentioned above, Section 1 has a total of 30 GLT columns whereas Section 2 has 96 GLT columns. The material quantities for the GLT Column is presented in Table 28.

Table 28 Material quantity for structural GLT

GLT size l x w x h (mm)	Total volume (m^3)	Density (kg/m^3)	Quantity (kg)	EPD Program	Country
115 x 180 x 2700	1.6	475.63	791	IBU	Germany
215 x 270 x 3200	17.5	475.63	8 312	IBU	Germany
Total					9 146.35

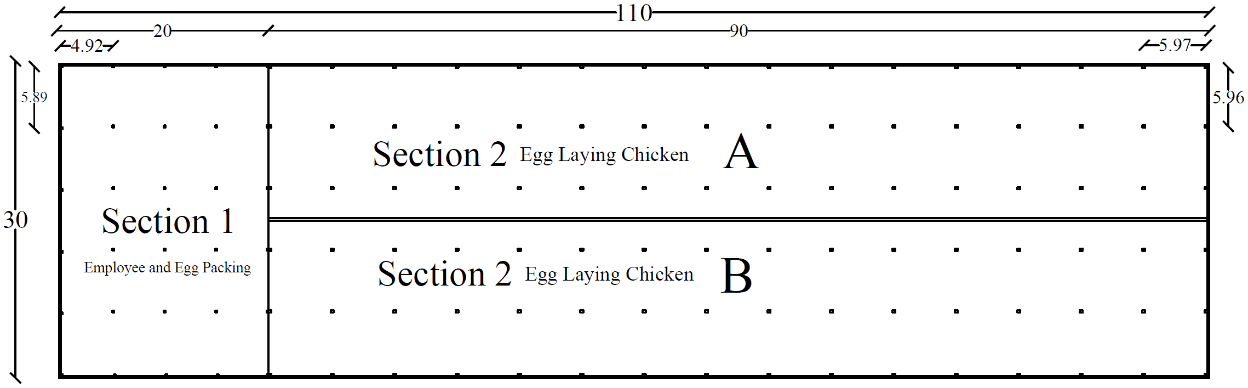

Figure 17 Illustration of GLT column arrangement, dimensions shown are in meter.

After estimating the GLT as a load bearing structure the wall assembly remains. In order to minimize thermal bridge, the wall assembly has to have continuous insulation throughout the building envelope. This means the structural GLT column will not interfere with the wall construction.

As depicted in Figure 9 to the left of the vapor there is an air cavity with studs. The air cavity allows breathing to prevent possible moisture-related damage. The wood studs have are 28 mm x 70 mm in size, which are used to fasten the wooden panel which serves as a façade along the exterior.

The size of the wood studs of the core structure is 45 mm x 90 mm. The spacing along the horizontal is 600 mm center to center, whereas in calculating the horizontal wood stud it is assumed along length of the wall, the intersecting point of the vertical stud and rows is not subtracted. Hence the number of horizontal wood stud for the wall with a height of 2 .7 m it is assumed to have three rows, one at the top, one at the bottom and one at the middle. Furthermore, for the wall with a heigh of 3.2 m it has four rails, one at the top, one at the bottom and two in the middle. This is done to add stiffness to the frame.

Based on this assumption the total number of wood studs is calculated as follows for both the core structure i.e. where the insulation is located and the wood stud along the exterior where air cavity with wood stud is indicated in Figure 9.

In order to clarify two walls with similar length which is 30 meter span of the building have height difference in the two sections, hence the letter A refers to the exterior wall in section one along the span of the building with a height of 2.7 m. Whereas the letter B refers to the exterior wall in section two along the span of the building with a height of 3.2 m. The material quantities for the wood studs is presented in Table 29 and Table 30.

Table 29 Wood stud along the exterior of the core boundary

Wall	Stud size	Total Vertical stud (pcs)	Total Horizontal stud (pcs)	Total volume (m^3)
Wall 30 m A	28 x 70 x 2700	51	3	0.4
Wall 30 m B	28 x 70 x 3200	51	4	0.6
Wall 20 m	28 x 70 x 2700	64	6	0.6
Wall 90 m	28 x 70 x 3200	302	8	3.2
Total				4.8

Table 30 Wood stud within the core boundary

Wall	Stud size	Total Vertical stud (pcs)	Total Horizontal stud (pcs)	Total volume (m^3)
Wall 30 m A	45 x 90 x 2700	51	3	0.9
Wall 30 m B	45 x 90 x 3200	51	4	1.1
1.13Wall 20 m	45 x 90 x 2700	64	6	1.1
Wall 90 m	45 x 90 x 3200	302	8	6.7
Total				9.8

A.2 Supporting Calculation for Section 4.9.10 Interior Wall for the Conventional Construction, Type 3

Based on the information gathered during the site visit this partition wall is a sandwich wall from Kingspan. After looking into Kingspan wall panel composition, recreating the wall layer by layer in Revit was tested. However, a better alternative was available. A Revit file of similar sandwich wall from Lindab is available for download and use from Bimobject. Hence for better data quality and reliable material export Lindab's sandwich panel is used to extract the material quantity from Revit. Lindab (n.d) describes the sandwich panel as composite of mineral wool base with a sheet metal covering. The sandwich panel is available in different sizes, the compatible size that aligns with the current construction is 120 mm sandwich wall panel.

Lindab (n.d) specifies the core density as 90 kg/m^3. This density is provided as an aggregate of the three layers which are sheet metal, insulation and sheet metal. Hence in order to quantify it based on this density the volume extracted by layer as shown in Table 31 is aggregated into one value, this is then mapped to and EPD in the One Click LCA environment. While mapping the material quantity to an EPD, a similar product is available in One Click LCA database. However, the density declared by the EPD in One Click LCA is 30 kg/m^3, since the environmental impact is calculated based on these critical values, the density declared by the EPD from One Click LCA has been used.

Table 31 material quantity in m^3 extracted from Autodesk Revit model

Material	Volume (m^3)	Density (kg/m^3)	Quantity (kg)	EPD Program	Country of Origin
Lindab Antique	0.61	-	-	-	-
Insulation	35.19	-	-	-	-

A.3 Supporting Calculation for Section 4.9.11 Interior Wall for the Biobased Construction, Type 1

The wall has a total length of 87 m, a height of 1 m and a thickness of 0.098 m. The vertical wood studs are spaced 0.6 m apart from center to center; in calculating the horizontal wood stud it is assumed along length of the wall; the intersecting point of the vertical stud is not subtracted. The number of horizontal wood studs for the wall is assumed to have two rails, one at the top and one at the bottom. Due to the complexity of modeling and integrating each wood stud in Revit, the material quantity for the wood studs has been estimated by hand calculation for the biobased construction type 1, 2 and 3. The material quantities are summarized and presented in Table 14, 15 and 16.

A.4 Supporting Calculation for Section 4.9.15 Roof Truss for Conventional Construction

Utilizing Alam (n.d.) Steelsolver website for educational purposes, the roof truss for the conventional construction was analyzed. The load mentioned in section 4.9.7 Exterior Wall was used in order to determine the stability of the roof truss. In addition to the loads the following setting were used to achieve an "ok" status in the member forces. The axial force distribution in truss members is presented in Figure 18 and the force distribution diagram is presented in Figure 19.

- Scissor truss with a size of 50 mm x 50 mm for the top chord, bottom cord and web members
- Region set to Europe and design code Eurocode 3
- Span 30 m
- Height 3.12 m
- Roof pitch 12^0
- Material type steel

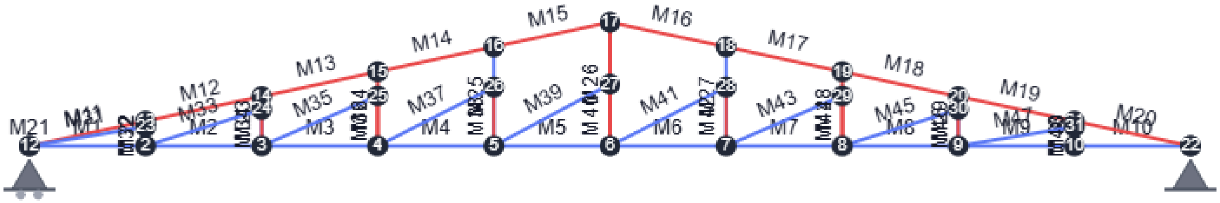

Figure 18 Scissor truss for the conventional construction 50 mm x 50 mm rectangular steel

The member force distribution shown in Figure 19 suggests that the steel structure is working as intended and the verifies the "ok" status achieved for each member. After looking into several manufacturers, the steel truss is spaced at a distance of 2.5 m apart, hence there is a total of 44 truss.

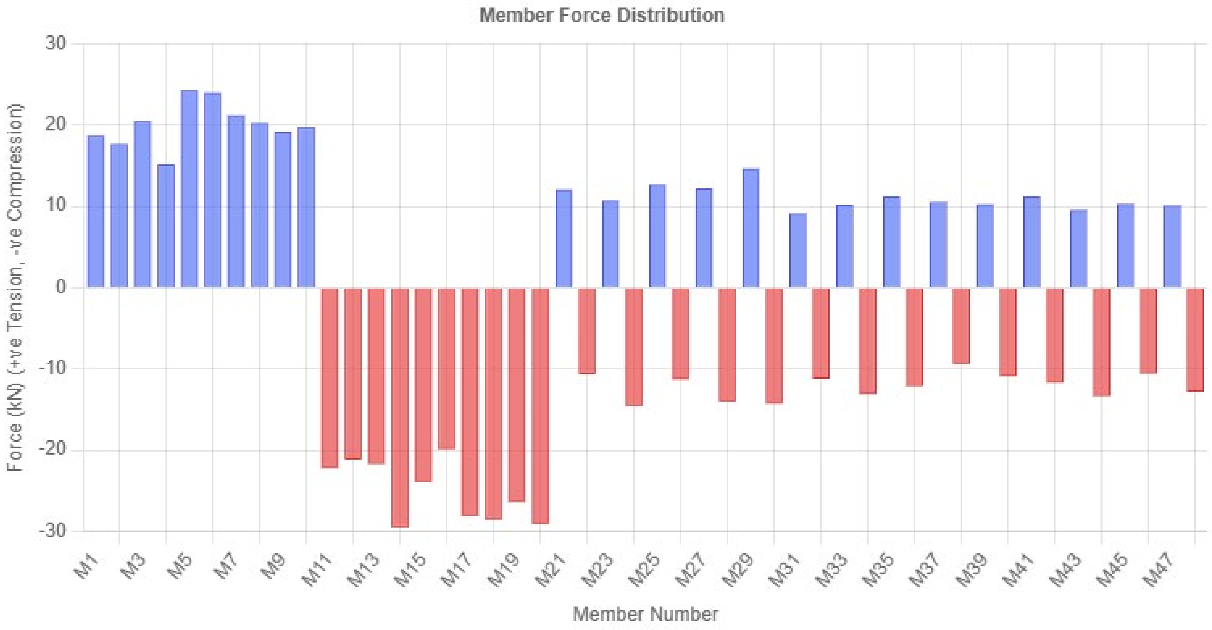

Figure 19 Force distribution of blue (tension) red (compression)

A.5 Supporting Calculation for Section 4.9.16 Roof Truss For Biobased Construction

The quantity of GLT is calculated manually. Simón-Portela et al. (2023) investigated the optimization of glulam beams and provided the dimensional specifications for a timber roof structure illustrated in Figure 20. Since the detail drawings of the roof structure were unavailable, the dimensions provided by Simón-Portela et al. (2023) is used to estimate the material quantity of GLT required for the roof and to conduct the LCA. The GLT truss is illustrated in Figure 20.

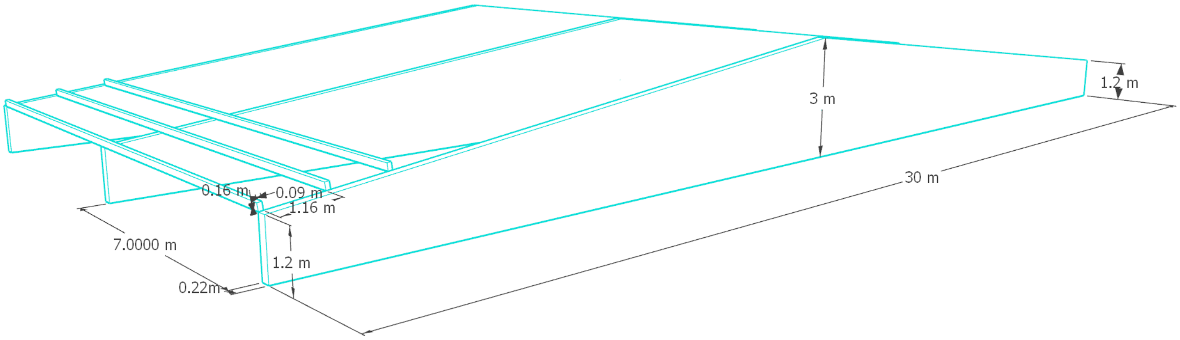

Figure 20 GLT roof truss spacing, dimension and structural consideration (Illustration done by author adopted from (Simón-Portela et al. 2023)

Furthermore, the assumption of dimensioning the roof truss has been validated by examining Swedish Wood (2022) as an additional source of information.

A.6 Supporting Calculation for Section 4.9.19 Door for Both Constructions

The number of doors categorized by section and type, is summarized in Table 32.

Table 32 door dimension, quantity and area

	Dimension w x h (mm)	Total quantity (pcs)	Total area (m^2)
Section 1 Type 1	2210 x 2010	2	8.8
Section 1 Type 2	1010 x 2110	1	2.1
Section 2 Type 1	1010 x 2110	4	8.4
Section 2 Type 2	1610 x2110	1	3.3
Total area (m^2)			22.6

A.7 Supporting Calculation for Section 4.9.20 Window for Both Constructions

The number of windows categorized by section and type, is summarized in Table 33.

Table 33 window dimension, quantity and area

	Dimension w x h (mm)	Total quantity (pcs)	Total area (m^2)
Section 1	1210 x 1810	7	15.3
Section 2	1205 x 805	29	28.1
Total			43.4

Appendix B Extended Data Table

A list of EPDs, including the EPD program, EPD identification number and the country of origin is presented in Table 34. In the table OCLD stands for One Click LCA ID which serves an internal identifier used within the One Click LCA database to reference and manage EPD datasets.

Table 34 List of EPD

Material	EPD Program	EPD Number or OCLID	Country
Crushed stone	OKOBAUDAT	0d61ff01-935e-4934-befe-cb0b2ea18187	Germany
Concrete	One Click LCA	680c8f3646bfdf1de1db9da8	Sweden
Reinforcement steel	OKOBAUDAT	f6861618-5a92-4c3a-94ba-9f7329b29662	Germany
XPS Insulation	One Click LCA	643c55c05b614a2bfdc2345b	Sweden
GLT	One Click LCA	688d081f40eb121e509f257c	Sweden
FRP Cladding	EPD Italy	65c4d3ca983a6f22d00a092a	Italy
Wood Stud	One Click LCA	6459eb9257b18e5cacfbd809	Sweden
CLT	One Click LCA	63f8695d0c9c017ecf062376	Sweden
Hemp fiber insulation	One Click LCA	640b5a4619b6e85290c9ea7b	Sweden
Vapor barrier	OKOBAUDAT	7b949ae4-3793-4670-86d8-241578803aa2	Germany
Purlin	One Click LCA	6459eb9657b18e5cacfbd811	Sweden
Catnic Steel Cover	One Click LCA	5bf348f48e202b0302eaa6d2	Sweden
Plywood	One Click LCA	688395c50c14770d3ec3f472	Sweden
Clay roof tile	One Click LCA	64ab01a33284ff6d5a402ac8	Sweden
Steel mesh partition	ZAG	6757016944f468440148f1ce	Germany
Sandwich Interior Partition wall	Utena Plant	6042530c8aa9fe205fa92c33	Lithuania
Door	One Click LCA	665767178d5a781a8990cd22	Sweden
Window	One Click LCA	655a4d9509b13f00fa86b356	Sweden