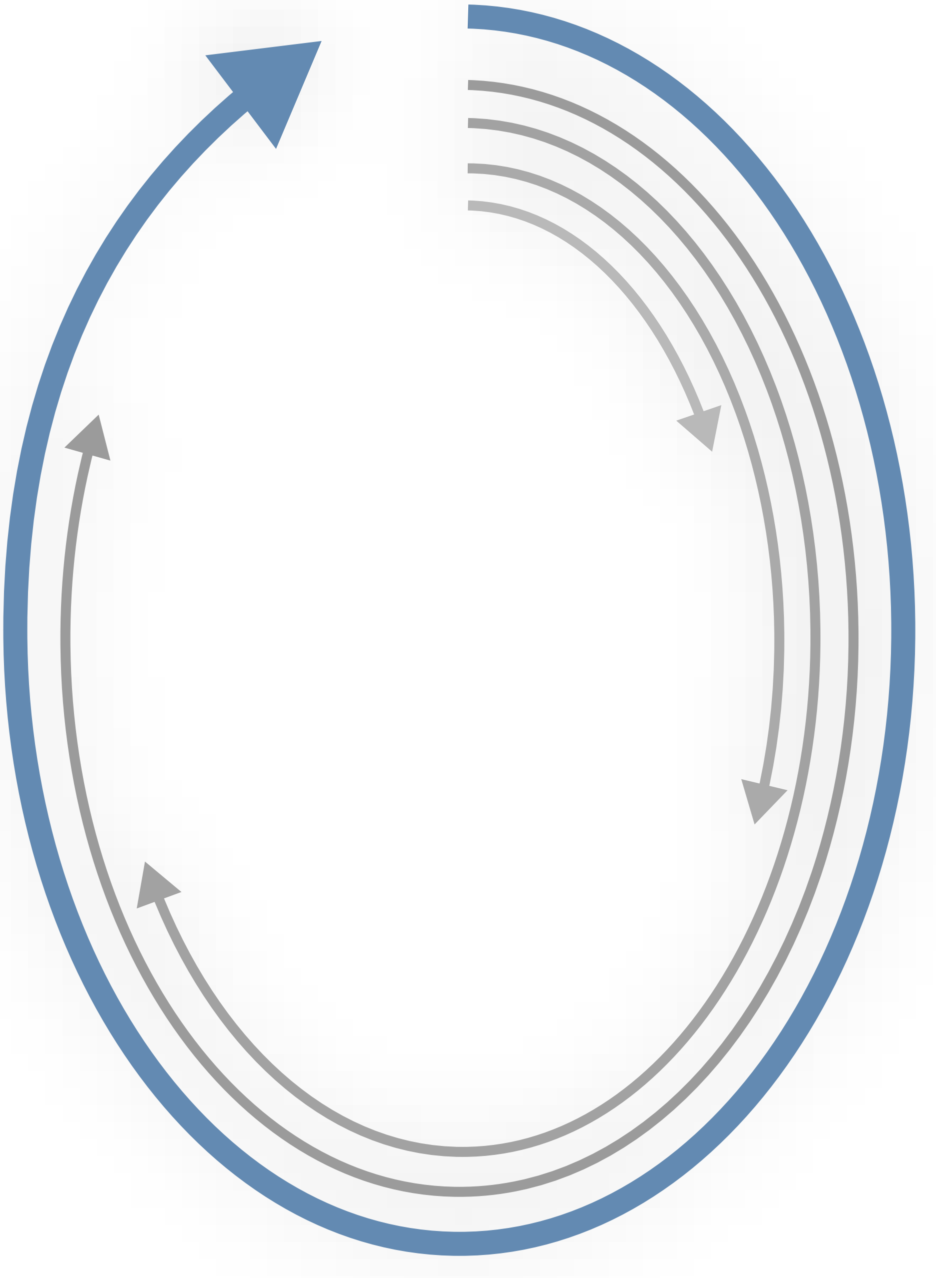
Towards **Zero Carbon** Buildings

Reducing the embodied carbon footprint of a construction



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> “The question that really matters is:
> how long can we go?
>
> In this era of Climate change, is it enough
> to just be sustainable?”

Acknowledgement

'Inspiration comes from our immediate context.'

This graduation thesis began with an inspiration from all the efforts put in by the campus of TU Delft and its esteemed docents. The actions taken towards climate change by TU Delft and the CRE department served as an important foundation for this research. Therefore, I would like to begin by thanking all those working on climate action, from where this thesis draws its inspiration.

Secondly, I would like to acknowledge my thesis mentors, Andy van den Dobbelsteen and Thaleia Konstantinou, who guided me through this research and helped shape this thesis in the best way possible. I would sincerely like to thank them for their constant guidance, introduction to further innovations and directing me towards the right resources. The two different guided approaches by Andy and Thaliea of looking at the bigger perspective while simultaneously thinking in depth allowed a holistic development of this thesis.

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Abstract

The building industry accounts for almost 40% of the total carbon emissions that are directly responsible for climate change. The buildings are now deploying energy-efficient solutions to lower carbon emissions from the operational phase. This adversely affects the share of embodied carbon emissions of building materials. The graduation thesis aims to study and compare the life cycle impact of different materials in building applications. The life cycle assessment method was adapted using certain assumptions to account for circular design approaches. End-of-life scenarios for all the materials were formed and compared using the assessment method. The analysis of materials in different building applications presented a significant difference between bio-based materials and other conventional materials such as steel, aluminium, and concrete. A reduction of almost 120% in the total carbon emissions of the studied building was estimated when bio-based materials were used over the existing materials. The proposed materials, along with energy recovery potential at their end-of-life, even showed the potential to achieve a carbon negative structural system. The proposed scenario of using bio-based material solutions in a building with a longer life span displayed better potential than a circular building construction. The role of biomass in mitigating climate change was thus highlighted.

Keywords: zero carbon, embodied carbon, carbon footprint, LCA, carbon sequestration, concrete carbonation, biogenic carbon, circularity, cradle-to-cradle

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00 | Glossary

Biogenic carbon: refers to the carbon content stored in nature-based products

Carbon emissions: used to refer all Greenhouse Gases (GHGs) responsible for global warming

Carbon footprint: used interchangeably with carbon emissions caused by any product or a process

Carbon negative: refers to the product or process that has net negative impact on the carbon emission level in atmosphere (removes carbon emissions from atmosphere)

Carbon sequestration: is a phenomenon of absorbing CO_2 from the atmosphere.

CO_2e (equivalent): It is a relative measure of heat trapped in any GHG

Embodied carbon: refers to the carbon emissions responsible from a building in its production and construction stage. This includes the carbon emissions from all the production methods of materials and resources involved.

EOL: End of life of a product when it reaches it service life age

EPD: Environmental Product Declaration is an ecolabel/ certificate that contains the LCI data for a product

GHGs: Greenhouse gases

GWP: Global Warming Potential is a declared unit of carbon emissions (usually in kgCO_2 equivalent)

LCA: Life Cycle Assessment is a method to check the environmental impact of any product or a process

LCI: Life Cycle Inventory is part assessment of any product to provide data that can be used in LCA

Low carbon: products or processes that emit low carbon emissions

MtCO_2e: 1 Metric tonne of CO_2 emissions equivalent

Operational carbon: refers to the carbon emissions during the operational phase of the building

SCM: Supplementary Cementitious Materials used in concrete as a replacement for ordinary cement

01 | Introduction

1.1 Background

Climate change is now the most critical issue around the world and all the industries are working towards sustainable measures to mitigate its effects. The UN Intergovernmental Panel released IPCC 2018 report highlighting the increased risk of catastrophic climate breakdown if the average global temperature increases to 2°C, instead of 1.5°C. Such threats would possibly lead to the destruction of the entire ecosystem (IPCC, 2018).

The United Nations Environment Programme (UNEP) is also working on measures to keep the average rise in temperature below 1.5°C. They have issued a Global Status Report 2017, focussing on the significant contribution of the building industry towards global carbon emissions. Since the building industry accounts for 39% of the total carbon emissions, UNEP announced a red alert for the industry to standardize zero-energy buildings globally within the next decade (Dean, B., Dulac, J., Petrichenko, K., and Graham, 2017).

Within this share, 28% of the emissions are caused by the direct emissions (i.e. Fossil fuel combustion) and indirect emissions (i.e. Electricity use and heating demand). Aside from this operational carbon emissions, 11% of the emissions occur in the production phase of the building materials. These emissions contribute towards, what is called embodied carbon footprint (Dean, B., Dulac, J., Petrichenko, K., and Graham, 2017).

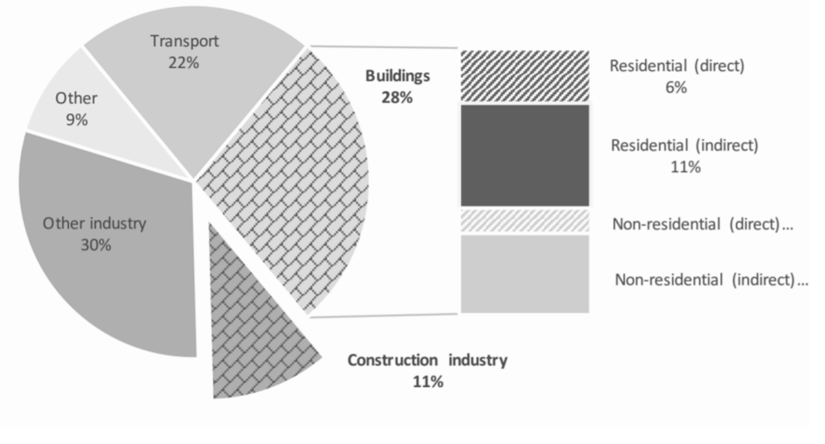


Figure 1: Share of global carbon emissions from different sectors (Dean, B., Dulac, J., Petrichenko, K., and Graham, 2017)

1.1.1 National and International Goals

The recent climate agreement (Klimaatakkoord, 2019) presented by the Dutch government sets a goal for 2030 to reduce the carbon emissions by 49% as compared to 1990 in the Netherlands. The Netherlands, among many other nations, has also endorsed climate neutrality goals for 2050, aiming to reduce carbon emissions by 95% as compared to 1990. As these goals are set out nationwide and for cross-sector monitoring of carbon emissions, they are bound to target the embodied carbon emissions.

World Green Building Council (WGBC) that also comprises of the Dutch Green Building Council (DGBC) as part of their Steering committee, released a report calling for urgent actions on carbon emissions. It states that ***by 2030***, all new buildings, infrastructure and renovations must have 40% less embodied carbon, and all new buildings must perform efficiently to achieve net-zero operational carbon. WGBC too addresses the need for full decarbonization of the sector, as highlighted in the IPCC report by setting up a vision ***for 2050***, which states that all new buildings, infrastructure and renovations must have net-zero embodied carbon, as well as net-zero operational carbon emissions (World Green Building Council, 2019).

1.1.2 TU Delft Carbon Roadmap

Apart from the goals set up by such international and national organizations, TU Delft has also been working towards the goal of carbon-neutral campus. A CO2 Roadmap for Carbon neutral campus, authored by Andy van den Dobbelsteen and Tess Blom, was published by the Campus and real estate department, TU Delft.

Among some other ambitions, one ambition of making the campus carbon neutral by 2030 was also formed. It implied that there shall be no GHG emissions arising from activities falling in either scope 1 (direct) or scope 2 (indirect) categories. Scope 1 emissions are defined as the direct GHG emissions as a result of using fossil fuels or similar resources. Scope 2 emissions are the indirect emissions used in the production of energy, or heating consumed by the campus. Lastly, scope 3 emissions are the accumulated emissions from the production of all other goods and services used by the campus. The other ambitions were to promote circularity, health and well-being, and biodiversity. However, to have a standard way of assessment CO2 equivalent of GHG emissions was generally used to present the findings.

The embodied carbon of materials used in the construction were compared with the emissions caused in a renovation. It was reported that in case of the Pulse building, embodied energy contributed to 64% of the total share. Therefore, to significantly reduce the carbon emissions, renovating existing buildings instead of constructing new ones was proposed as one of the solutions. However, the need to have new infrastructure for growing campus still pose a challenge in reducing the embodied carbon emissions. As part of this research, a new campus building in TU Delft would be studied to tackle this challenge.

1.1.3 Comparison of an efficient and low-energy building

The life cycle energy of any structure can broadly be classified into two categories- operational energy and embodied energy. While operational energy depends on the performance of the building, occupant behaviour, and comfort levels of users; embodied energy entails the production energy, and transportation energy went into the construction materials. Similarly, carbon-dioxide equivalent (or CO_2e) can be classified into operational and embodied carbon footprint of the building.

A comparative study between operational and embodied energy of an old office building was performed by Cole & Kernan (1996). It implied that embodied energy constituted for 4-9% energy of 50 years life-cycle energy demand of the building. More studies from the 1990s estimate that if the life span of a building were around 100 years, then the embodied energy would further reduce to about 2-2.5% of the total energy consumption. This eventually resulted in shifting the attention of sustainability goals towards reducing the operational energy (Ibn-Mohammed et al., 2013).

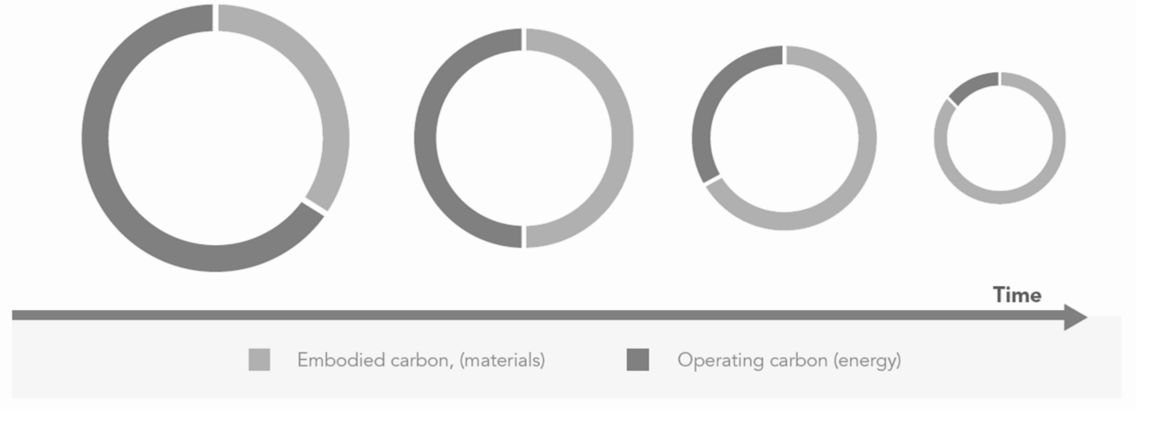


Figure 2: Trend of embodied carbon and operating carbon in buildings over time (Bionova Ltd/One Click LCA, 2018)

At present, with all the new developments over the past few decades in insulation types, advanced efficiency of HVAC systems, and smart technologies; the green and sustainable constructions are reaching zero energy design goals. However, they demand increased material requirements for thermal mass or improved insulations that require more production energy. Thereby increasing the relative embodied energy of materials (Gilbert, 2018; Ibn-Mohammed et al., 2013; Maassarani, Mohareb, & R., 2017).

A set of studies ranging from residential to non-residential buildings from different countries were studied by Ibn-Mohammed et al. (2013). It concludes that the proportion of embodied emissions to total lifecycle emissions varies drastically due to different construction methods, building types, and geographical locations. However, the trend of increased embodied emissions as a result of reducing operational energy can be established.

1.2 Problem statement

All the national and international organizations are working towards the goal of decreasing carbon emissions to limit the rise in global temperature to 1.5°C. As the building and construction industry are the most significant contributors to these emissions, Green Building Councils have further set up their goals to achieve net-zero energy buildings by 2030. With advancements in the building industry towards achieving net-zero energy goals, the operational carbon emissions from the building have reduced remarkably. However, in this process of development, ***the share of embodied carbon footprint increases.***

In addition to assessing and designing strategies to reduce operational energy, the carbon emissions from embodied energy of materials must also be addressed. The choice of high-carbon materials eventually increases the total carbon footprint of the building.

1.3 Objectives

The main goal of this research is to propose solutions that can lower the embodied carbon emissions of a building. The research focuses on contributing towards the goal of carbon-neutral TU Delft campus. As the challenge of increased embodied carbon emissions is faced by new zero-energy buildings, a case example of Echo building in TU campus is selected for the research. Echo building is currently in design phase and proposed to be an energy-positive construction. This gives an ideal opportunity to perform a comparative analysis of the impact from building materials on embodied carbon footprint. Further ahead, material alternatives would be proposed to reduce the total carbon footprint. The conclusions drawn from this research would also be presented in form of design guidelines to benefit the next planned building in TU campus.

A hypothesis is proposed to achieve zero embodied carbon goal using materials that sequester carbon either artificially or biologically in their production phase. Research on artificial sequestration is based on the new solutions using strategies such as carbon mineralisation or carbon activation. This is further explained in Section 2.3.

Research boundaries

a. As the research focuses on impact of building industry on carbon emissions, this research would aim to study the single indicator of CO_2 equivalent in Life cycle analysis, and not others such as SOx or NOx equivalent.
b. Building materials are responsible for the majority of carbon emissions in the embodied carbon footprint of the building (Nässén, Holmberg, Wadeskog, & Nyman, 2007). Thus, the case example in TU

Delft would focus only on the building materials and not the other emissions arising from HVAC/ Lighting equipment.

c. The goal of carbon neutrality usually entails vast boundaries such as the food wastes and travel footprint of users too. However, most building councils define zero carbon buildings as the ones that offset their embodied carbon emissions from building materials and construction. Therefore, this research would use the theoretical energy performance indicators and energy production from renewable sources on site, to evaluate the offset time for total carbon emissions of the case study.

1.4 Research Question

The main research question of this graduation project is:

What alternate materials and strategies can be used in building design that can lower the embodied carbon footprint to meet zero carbon goals?

The research would answer the main question through the following sub-questions:

1. What are the existing and new low-carbon material alternatives to lower the embodied carbon footprint of a building?
2. What are the current assessment methods to evaluate the carbon footprint of a material and a building? Are there any gaps in the current method and if yes, what are those?
3. How can the assessment method be adapted to include circularity and cradle-to-cradle approach to study the actual impact of building materials?
4. How much carbon emissions are caused by different life stages of a material and how do they compare with the other materials?
5. How much impact on the total carbon footprint of Echo building is created by the use of such low carbon materials?

1.5 Approach and methodology

The graduation project is divided into 3 phases: literature and market research, defining assessment method and conducting analysis, and design proposal.

- ### Literature and market research

Literature study is further divided into two parts: material research and Life Cycle Assessment methods. Material alternatives are studied both from existing literature and online sources. While literature on nature-based low embodied energy materials are abundantly available, other material options from artificial carbon capture method are studied from the available market data. It is acknowledged that many new materials are currently researched all over the world, but due to the lack of literature available in English language, only few materials could be studied. Data from material companies were also collected to assess them further.

Various software and databases are available to perform Life Cycle Assessments (LCAs). Literature study on LCA is conducted to understand limitations, benefits, and procedure of the method. Excel databases such as that of Ecoinvent and free software such as openlca or One Click LCA are used to assess the materials and building.

Apart from the literature studies, Campus and Real Estate (CRE) department of TU Delft campus is contacted to obtain the data of the case example (i.e. *Echo* building) in TU Delft campus.

- Defining assessment method and conducting analysis

The shortcomings of existing LCA assessment methods are reported. Learnings from the literature studies and different LCA software are applied to define an assessment method. This is done to compare all the conventional and new materials with a consistent scope. Additional parameters unique to certain materials such as carbonation of concrete or hempcrete, are identified and explained. Besides this, the uncertainty and approximations are reported in the section 5.6.

The life cycle stages of materials researched in literature study are explained, along with the assumptions made for each LCA module. Data from Echo building is deduced into the total material quantities for specific building application, such as columns, beams, slabs, etc. Material options for each building element are analysed as per the assessment method and compared to each other. With the data collected for all building elements and their suitable material choices, the results are interpreted. The impact of different building elements is also shown together as parts-of-total carbon footprint graph. This would emphasize the difference in their impacts and provide inputs for identifying hotspots in a building.

- Design proposal

The suitable material options for different building elements are combined to form sustainable design solutions, specific to different scenarios. The design solutions are presented as conceptual details and guidelines not just for Echo building, but also for other new/ renovation projects.

1.6 Societal and Scientific relevance

This graduation project aims to bring awareness about imminent problems for net-zero buildings and propose solutions based on the technological advancement in materials around the world. This research intends to influence design process in upcoming buildings of TU Delft campus to achieve carbon neutrality by using low carbon materials. The conclusions would also influence the larger audience in the architecture industry to shift towards environment-friendly material options for construction gradually.

The building industry has only recently started to focus on the issue of carbon emissions resulting from construction materials. As several industries are acting as influencers in design, it is easier for a building design to deviate from the actual bigger problem. The materials supplied by manufacturers also take support of green labels to influence the designers to make sustainable choices without understanding the bigger picture. The research expects to put light on the importance of complete life cycle assessment of materials and their impact on the environment. By comparing and proposing alternate materials, an emphasis would be made on the need to lower the embodied carbon emissions.

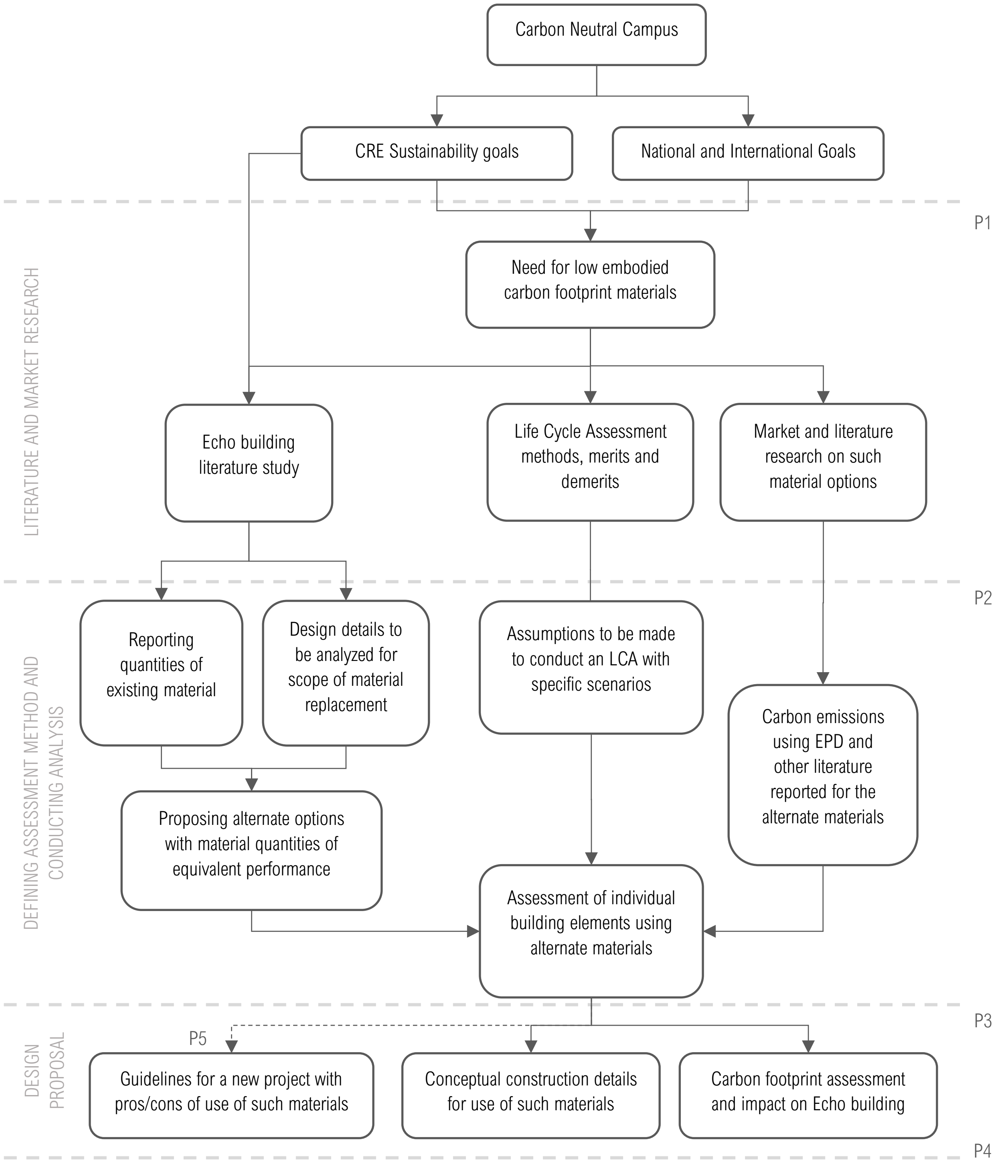


Figure 3: Methodology flowchart diagram

02 | Zero Carbon building strategies

2.1 Definitions and terminologies

2.1.1 Energy vs Carbon

The term 'energy' and 'carbon' is frequently used in the discussions of high-performance buildings. The two terms are often interchangeably used as well, especially in the context of operational and embodied performance indicators. For instance, both embodied energy and embodied carbon of materials are used in the discussion of efficiency of buildings. It should be well noted that these terms quantify the impact of built environment but in different indicators.

The term 'carbon' is an abbreviation of impact indicator carbon equivalent that indicates the Global warming potential from all the Greenhouse gases. On the other hand, 'energy' is used to quantify the non-renewable or renewable energy used in a process. The terms are still directly proportional in the case of operational assessment. However, the embodied energy and embodied carbon cannot be calculated from each other. This is because any non-renewable energy used can be expressed in terms of carbon equivalent. Thus, the operational energy of a building remains proportional to the operational carbon emissions. In other words, as the operational energy increases, the operational carbon also increases by the same factor. On the contrary, embodied energy and embodied carbon may be completely different from each other. This is due to the direct emissions or sequestration of carbon dioxide from processes involved in the material production (Ayaz & Yang, 2009; Ibn-Mohammed et al., 2013). For instance, cement releases carbon dioxide in its manufacturing process, while trees use carbon dioxide in photosynthesis to provide wood. Another example from recent studies of concrete production could be taken, wherein excessive energy is used to capture and store carbon dioxide in concrete. This would lead to a high embodied energy but low embodied carbon of the end product.

2.1.2 Net-zero energy vs Zero carbon

Nearly zero energy buildings (NZEB) or commonly known as 'net-zero energy' buildings are defined differently by various organizations. The standard definition that underlies in all of them define them as high performance buildings with very low energy demand. Furthermore, they make use of on-site or off-site renewable energy sources to cover their demands (Attia, 2018). Almost all the definitions address the operational energy use of the building.

On the other hand, 'zero carbon' buildings currently do not have a standard definition and is defined differently by different organizations. While some relate it to the zero energy buildings with zero carbon emissions in the operational phase, others include the embodied carbon emissions as well (Bionova Ltd/One Click LCA, 2018; UKGBC, 2019; World Green Building Council, 2019). Even among the ones that include embodied carbon emissions, the assessment period over which the building achieves carbon neutrality using renewable sources, is unclear. In this report, the term 'zero carbon' for a product would be used to refer to an overall zero impact on carbon emissions in the atmosphere, over the specified time period.

2.2 Existing strategies to achieve zero carbon buildings

The embodied carbon emissions have recently caught up more and more attention by many researchers and organizations around the world. As they contribute to a significant amount in the total share of carbon emissions, various strategies to reduce the embodied carbon emissions are provided by different Green Building Councils such as WGBC, DGBC, UKGBC and more. (UKGBC, 2019; World Green Building Council, 2019) .

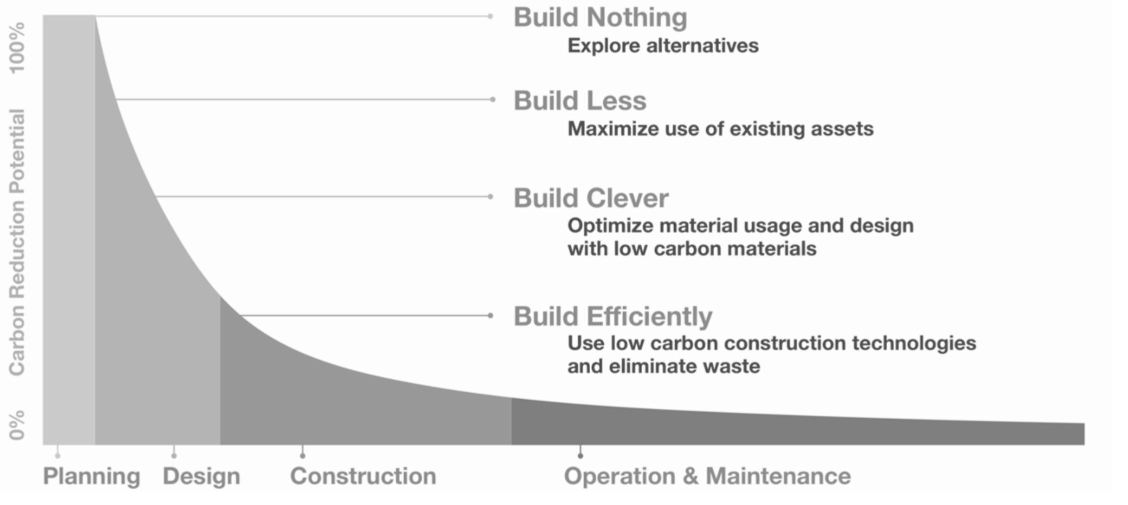


Figure 4: Impacts of different design approaches on carbon reduction potential (Source: World Green Building Council, 2019*)*

a. Prevention

As the carbon roadmap of TU Delft campus also suggested, the use of existing buildings must be promoted to avoid the carbon emissions arising from new constructions. Figure 4 explains the carbon reduction potential of different strategies. The highest potential in reducing the carbon emissions is in prevention of new construction followed by renovation or reuse of existing structures.

b. Reduction

The new construction should be designed in such a way that it reduces the overall impact of carbon emissions. This can be done in following ways:

- Optimizing design to reduce the demand for materials
- Using locally available materials, if possible, to reduce the transportation burden
- Using low carbon materials while conceptualizing design
- Maximizing the use of materials produced from renewable source of energy
- Practising zero-energy design strategies to reduce the operational carbon emissions

c. Carbon sequestration

Canada Green Building Council (2020) suggests that carbon sequestration in some building materials could serve as a potential solution to reducing the embodied carbon emissions. They have also reported that some of these materials may even have the potential to store more carbon than emitted in their primary production. This could result in achieving negative carbon footprint for building materials. Carbon sequestration is further discussed in Section 2.3

d. Designing for Future

Design strategies that consider future scenarios of the building also have the potential to either increase the lifetime of the building or provide better end-of-life solutions. Strategies such as Design for adaptability (DfA) could ensure flexible use of spaces resulting in prolonged lifetime. Other strategies such as Design for Disassembly (DfD) could reduce the energy consumed in demolition/ deconstruction of the building, and also facilitate circular use of building materials.

e. Offset

The residual carbon footprint from embodied carbon emissions could finally be offset either as an equivalent of renewable energy produced or from other offset schemes approved by the local building council.

2.3 Carbon sequestration

There are various and often misunderstood terminologies related to carbon absorption. Some of them used in this research are carbon sequestration, biogenic carbon, carbon sinks and carbon source.

Carbon sequestration is a phenomenon of absorbing CO_2 from the atmosphere. Natural processes such as photosynthesis in plants, trees and soil cause them to sequester carbon dioxide from the atmosphere. Such CO_2 sequestered or emitted from the biological sources such as plants or trees are known as ***biogenic carbon***. Similarly, oceans and aquatic life sequester carbon through different chemical and biological processes. In doing so, they become ***carbon sinks*** that locks carbon and avoid it from being released as a GHG in the atmosphere. A material can act as a carbon sink for a several years in form of a rock or just a few days in form of a plant before it is eaten and released back in the atmosphere through respiration. Conversely, ***carbon sources*** release the carbon into the atmosphere. Carbon emissions from the use of fossil fuels are the common carbon sources. Some carbon sinks such as forests and soil also act as carbon sources (Kayla Delventhal, 2017; Keenan & Williams, 2018; Wreglesworth, 2019).

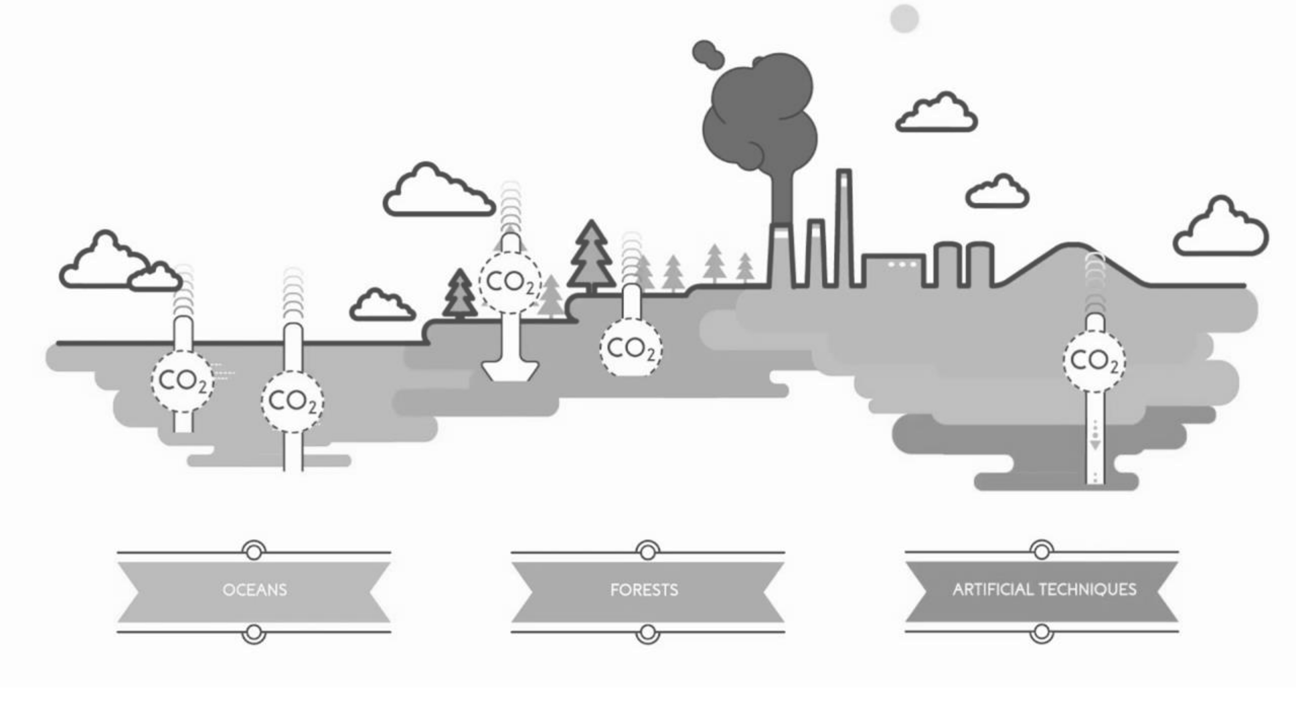


Figure 5: Types of Carbon sequestration (Source: https://www.activesustainability.com/climate-change/carbon-sniks-what-are/)

Carbon capture and Storage (CCS) is another process being carried out in many parts of the world. This process captures the CO_2 at the carbon source sites and compresses it in order to transport it to a storage facility. It is then commonly injected in underground geological formations, to prevent them from getting released into the atmosphere (Bouzalakos & Maroto-Valer, 2010; Kools, 2018; Sanna et al., 2014). Figure 4 illustrates the carbon cycle from source to the sinks via CCS system using few examples.

Although CCS method is essential in achieving the goals of reducing carbon emissions, it comes at significant costs and might impact the ecology, since using ocean as a carbon sink causes acidification, if exceeded (Huijgen, 2003; Wreglesworth, 2019). Thus, use of materials that can lock away carbon in form of building elements has gained attention by professionals over the past few years. Such materials are formed either by biological sequestration or artificial sequestration methods.

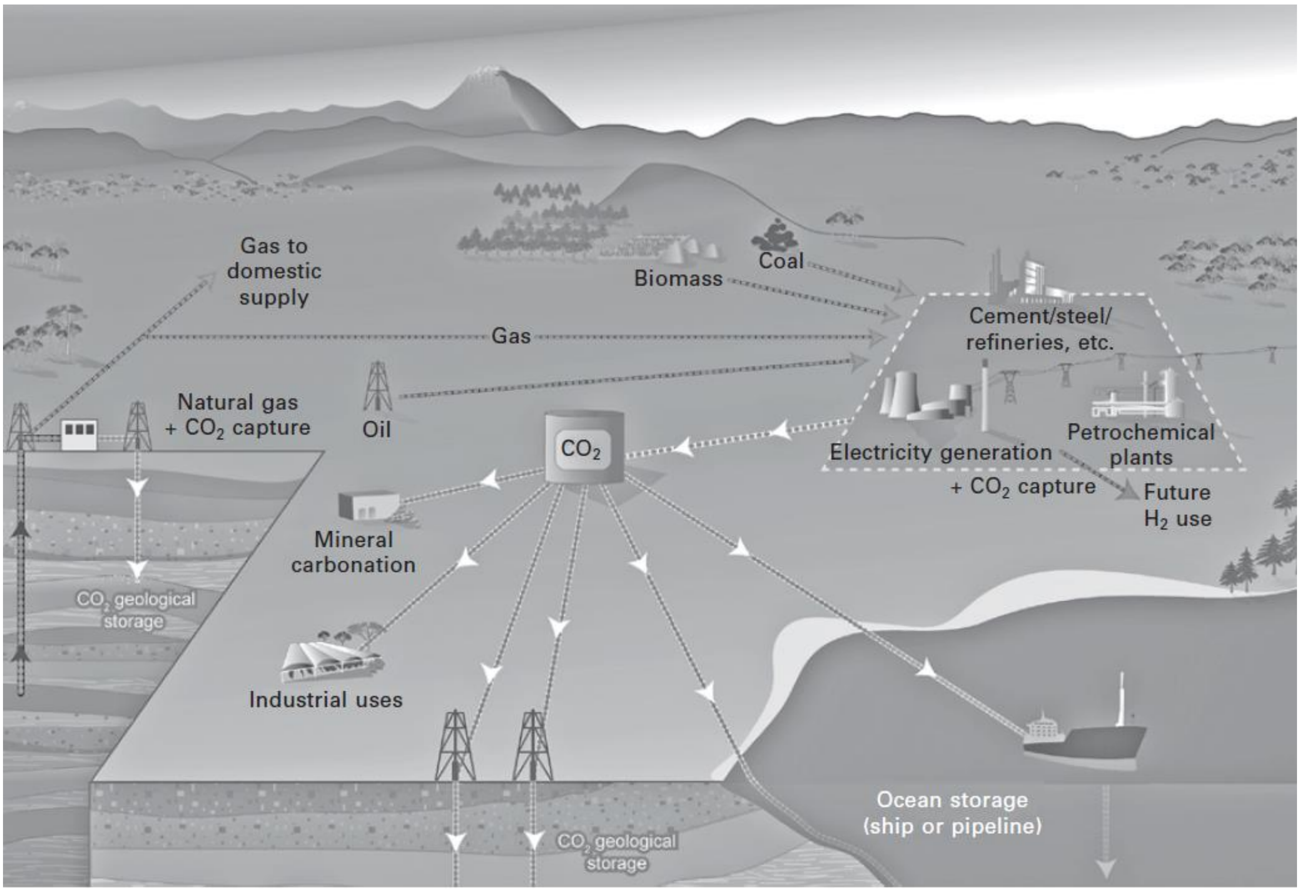


Figure 6: Schematic diagram of CCS system showing the carbon cycle between the sources and sinks (IPCC, 2018)

2.3.1 Biological carbon sequestration

As discussed, bio-based materials (such as trees, bamboo, etc) go through the process of photosynthesis to store biogenic carbon within their stems, leaves and roots. Although several factors affect the amount of carbon sequestered in a tree, a thumb rule adopted by carbonify.com is followed. It states that a ton of CO_2 is sequestered by 5 trees of 40 years age, also taking into account that some trees are destroyed before 40 years (Carbonify, 2015).

The use of such bio-based materials have been identified as common sustainable strategies to reduce the embodied carbon footprint of a building, as they require less energy in production phase and believed to be carbon positive. Peñaloza (2017) argues that the assumption of bio-based materials being carbon neutral might be an oversimplification. The assessment of carbon cycle before the harvest of trees are usually unaccounted, which leads to optimistic results for a building. As harvesting activities in agriculture and forestry also leads to carbon emissions, the net result may also be contradictory. Figure 7 shows a comparison of carbon footprint of concrete and timber construction in the most optimistic and pessimistic scenarios. He concludes that the impact of using bio-based materials is always lower than other materials such as steel or concrete. However, the gap between their impacts reduce when different approaches are adopted to assess carbon footprint.

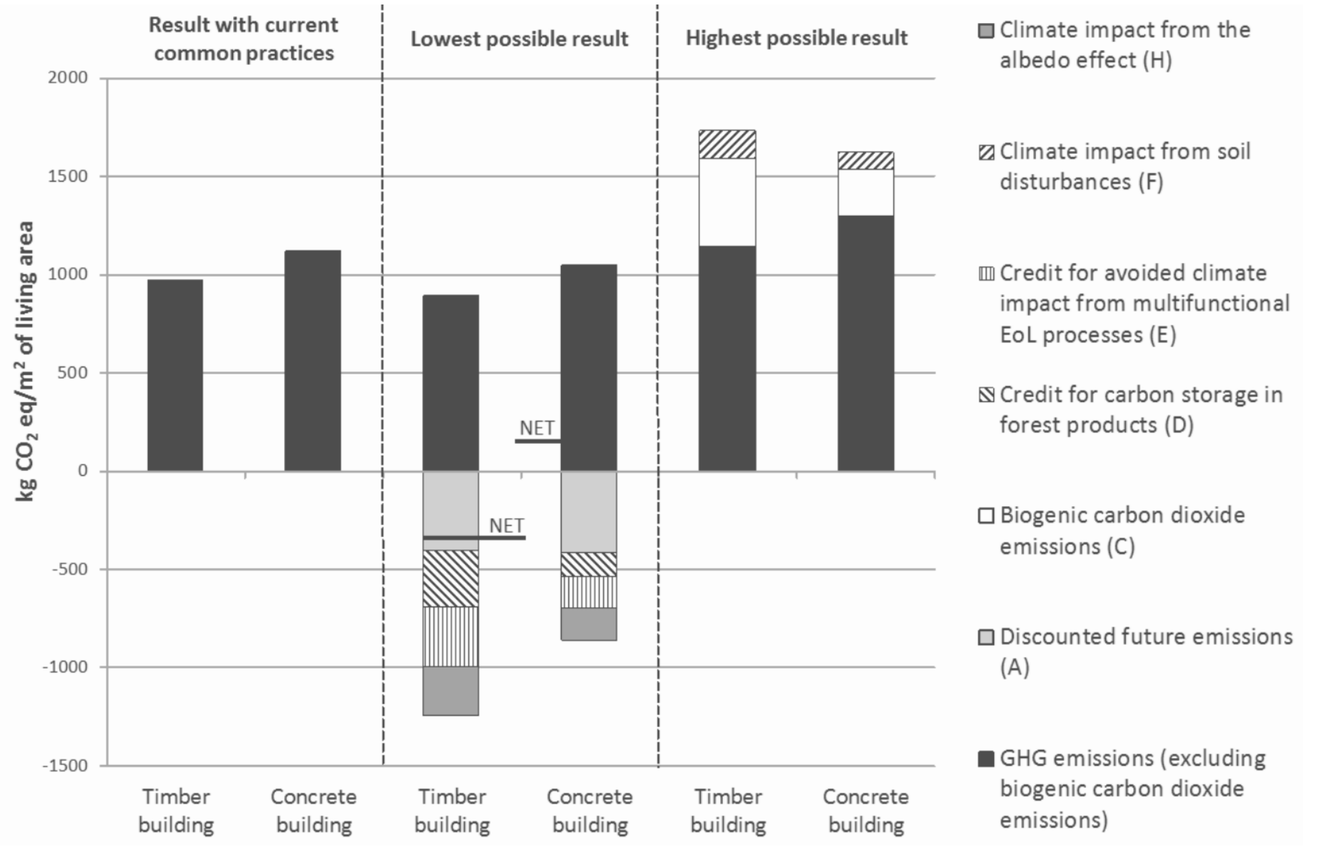


Figure 7: Comparison of carbon footprint of concrete and timber construction, accounting several factors from forestry (Peñaloza, 2017)

2.3.2 Artificial carbon sequestration

An intermediate step of CCS method is separation of CO_2 from other flue gases, that makes the process slightly expensive. Other technologies such as carbon mineralisation have the advantage of skipping over this step and directly use the captured flue gas emissions. They sequester CO_2 in an exothermic reaction producing stable carbonate products (Kools, 2018). More innovative methods of sequestering CO_2 to form building materials are studied by various institutions and companies. Some materials produced from such methods are presented in section 3.2 along with their environmental impact and economic feasibility.

2.4 Summary

Different terms related to carbon and energy parallelly exist with many interpretations. The terms zero carbon and zero energy are often used interchangeably, but with the same intentions of defining sustainable and efficient buildings. For this research, the terms are defined distinctively with 'carbon' being an impact indicator of Global warming potential, caused by all the Greenhouse Gases (GHGs). It is measured in equivalence of carbon dioxide ($kgCO_2$). On the other hand, 'energy' stands for the non-renewable and renewable energy used in the processes. This research focusses only on the carbon emissions from the materials used in buildings, i.e. embodied carbon footprint.

Some existing strategies to reduce the carbon emissions in construction already exist. These are translated into ***broad approaches- prevention, reduction, sequestration and offset***. While some strategies have already been in use when designing buildings, ***carbon sequestration in building materials is a novel approach***. It is believed that such strategies may be the only solution for climate change.

Biological carbon sequestration is a natural phenomenon that already occurs around us in the oceans, trees, and soil. However, the potential of using bio-based building materials has only been realised recently to combat carbon emissions in the atmosphere. Contrarily, artificial carbon sequestration is a relatively newer method of producing materials that could store carbon dioxide within themselves.

03 | Low carbon materials

3.1 Bio-based materials

Bio-based materials are considered to have economic and environmental benefits in building construction. Since they are attributed as renewable material source, they are widely accepted as a substitute to high embodied energy materials. Such materials are produced from different sources such as forest based, plant based or vegetable fibre based (Paiva, Caldas, & Toledo Filho, 2018).

3.1.1 Forest based materials

As discussed before in section 2.1.1, use of timber can even have negative unforeseen impacts on the carbon emissions from the forestry. Assuming that the timber obtained from forests is harvested sustainably as per the guidelines set by forest councils, it can be accredited with carbon positive impacts.

a. Wood

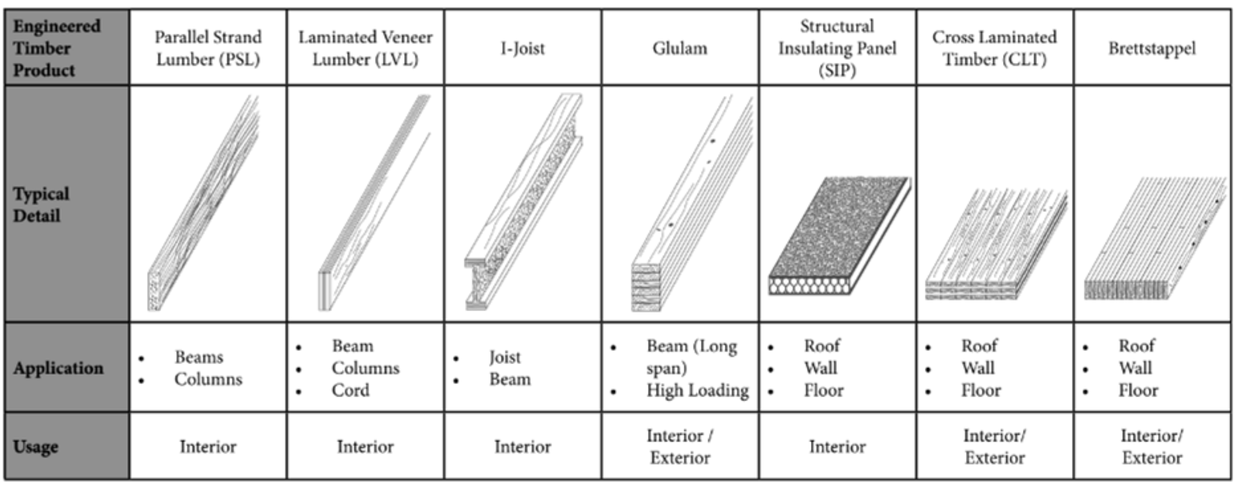
Softwood materials can be defined by the European codes as below (Ramage et al., 2017):

- EN 14081: Solid construction timber
- EN 14080: Glued-laminated timber
- EN 14915: Solid wood for wall and façade panel
- EN 15497: Finger-jointed timber

Figure 8 shows the typical engineered wood and their structural applications in European context. Below is the list of some engineered wood products and their applications:

- Glulam and Laminated Veneer Lumber (LVL): used in lightweight wood frame constructions as beams and rafters, trusses, etc.
- Oriented Stranded Boards (OSB) and Medium density fibre (MDF) boards: used in wood panelling, roof sheathing, floor sheathing, insulations, etc.
- Cross-Laminated Timber (CLT): used in Solid timber constructions as shear walls, braced truss frames, etc.
- Structural Insulating panels (SIPs): consists of Expanded Polystyrene (EPS) sandwiched between OSB, and used in place of stud wall

Engineered products are preferred in medium-large scale buildings due to their higher structural strength, but the adhesives used in their production methods lead to a higher embodied energy (Figure 10)(Ramage et al., 2017).



Engineered Timber Product	Parallel Strand Lumber (PSL)	Laminated Veneer Lumber (LVL)	I-Joist	Glulam	Structural Insulating Panel (SIP)	Cross Laminated Timber (CLT)	Brettstappel
Typical Detail							
Application	• Beams • Columns	• Beam • Columns • Cord	• Joist • Beam	• Beam (Long span) • High Loading	• Roof • Wall • Floor	• Roof • Wall • Floor	• Roof • Wall • Floor
Usage	Interior	Interior	Interior	Interior / Exterior	Interior	Interior/ Exterior	Interior/ Exterior

Figure 8: Structural engineered wood classification (Ramage et al., 2017)

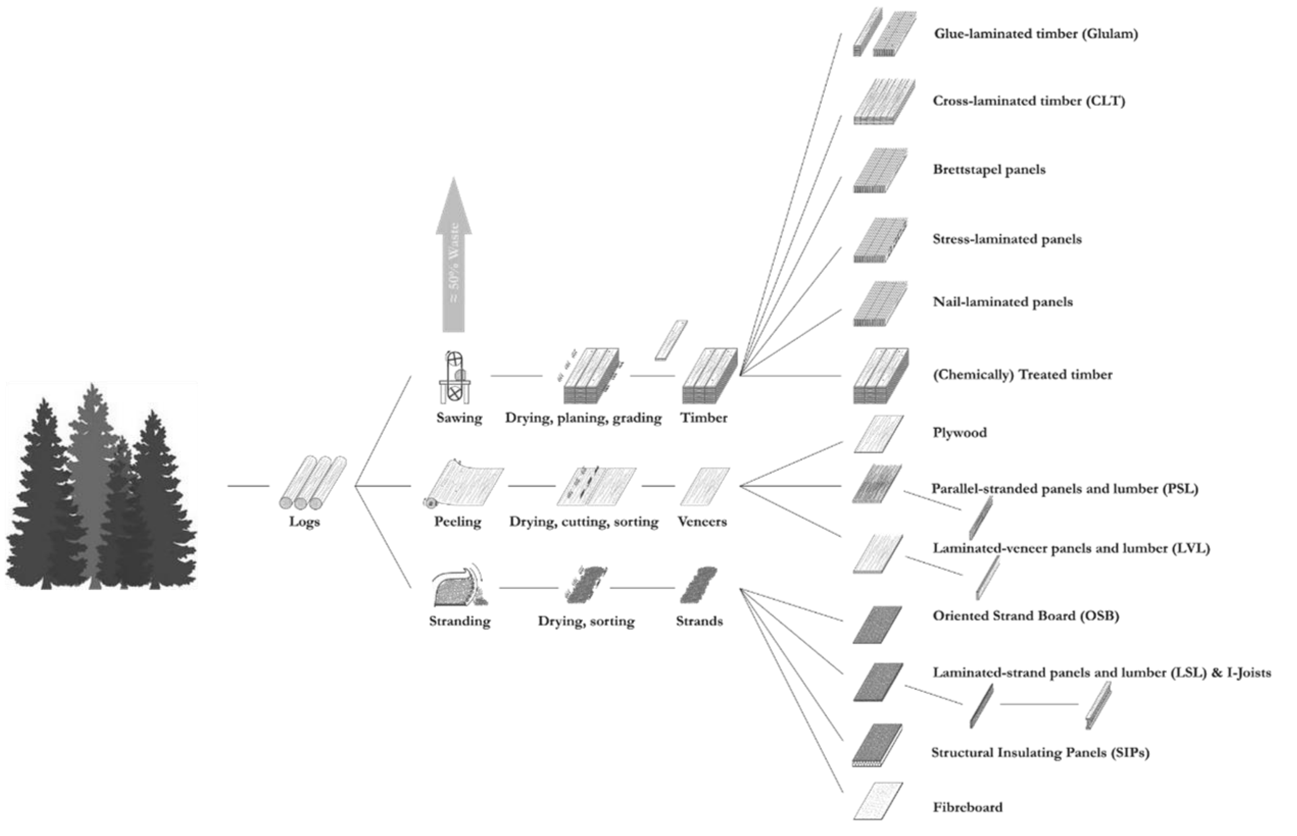


Figure 9: Forest wood products from different production methods (Ramage et al., 2017)

Life span and End-of-life scenarios

Most structural wood products are treated such that their life span is enough to be assumed similar to other structural materials in the building. A principle of cascaded use is proposed by European Parliament for wood. It suggests that after the primary use of wood, it should be reused/ recycled, then be combusted for energy or finally be put in the landfill (Ramage et al., 2017).

Although, landfill is neither environmental-friendly nor economical, therefore it is hardly ever practiced. On the other hand, combustion to generate energy is attributed as an essential form of energy production in Europe (Peñaloza, 2017).

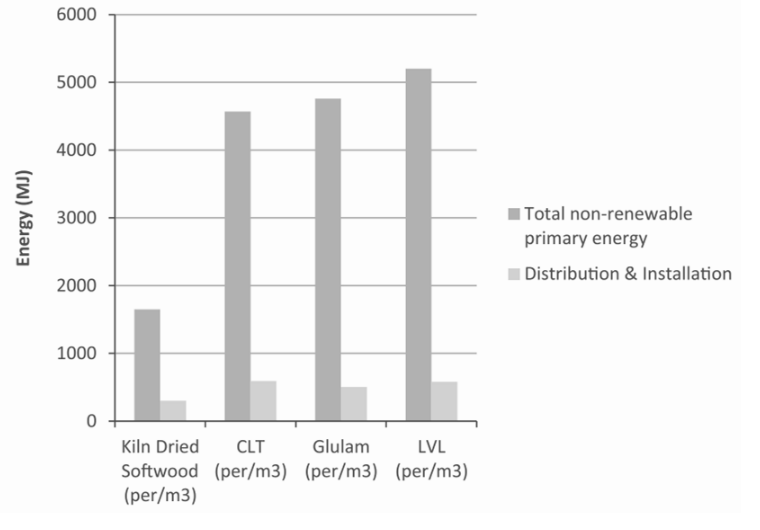


Figure 10: Contribution of adhesives in embodied energy of engineered wood (Ramage et al., 2017)

b. Bamboo

Bamboo has widespread application and grows at a higher speed, making it another suitable alternative. Three industrial bamboo products commonly available at production facilities of bamboo are (Vogtländer & van der Lugt, 2015):

- **Ply bamboo:** Bamboo strips are compressed and laminated to produce ply bamboo that are used as beams, flooring panels or wall panels
- **High density bamboo:** Rough bamboo strips and fibres are soaked in resin and compressed in moulds to form high density material. It is as durable as tropical hardwood and thus, can be used as non-structural beams, flooring material or outdoor decking.
- **Flattened bamboo:** A more efficient way of producing bamboo boards is by using bamboo step longitudinally and compressing it in flat boards. They use less adhesive and produce lesser waste. They can also be used in flooring.

Life span and End-of-life scenarios

Like wood, bamboo products manufactured as per standards for structural use are assumed to have a life span equal to other structural materials. A more substantial proportion of bamboo products are assumed to be combusted for heat and electricity production than wood (Vogtländer & van der Lugt, 2015).

3.1.2 Plant and vegetable-based materials

Alternatives to reduce cement in the production of concrete are researched and experimented in the academic industry. Plant and vegetable-based building materials such as hemp, rice husk or flax have shown potential when added with mineral binding materials to form sustainable forms of concrete (Amziane, 2016; Paiva et al., 2018). While many researches are further away from showing promising results, one solution has gained attention in the past few years due to its remarkable properties- Hempcrete.

a. Hempcrete

Among other plant-based materials, hemp has also widely been accepted as a building material that is used with lime-based binder. They are combined to form a non-load bearing material that can be used in different methods of construction. Hempcrete shows good thermo-acoustic insulation and hygrothermal properties (i.e. Material can change its physical properties to adapt temperature and moisture changes). Besides sequestering CO_2 in the growing phase of hemp, hempcrete also absorbs carbon throughout its lifetime improving its mechanical properties (Arrigoni et al., 2017; Pretot, Collet, & Garnier, 2014).

Figure 11: Hempcrete blocks produced by Isohemp (Source: https://www.isohemp.com/en/hemp-blocks-buildings-hempro-system)

Figure 12: Hempcrete cast-in-situ method (Stanwix & Sparrow, 2014)

New researches are still exploring further possibilities of its application. Some of the practiced solutions are (Stanwix & Sparrow, 2014):

- Cast-in-situ: The hempcrete mixture is poured in between temporary or permanent formwork for walls. It has excellent insulating properties and thus, is also used in flooring or roofing.
- Spray-applying: The mixture is also sprayed on walls to improve insulation.
- Precast hempcrete blocks and panels: Easing the process required on site, factory-made blocks and panels speed up the process of construction. However, their insulation properties differ from the in-situ methods.

Life span and End-of-life scenarios

Due to the carbonation process of hempcrete throughout its lifetime, it acts as a carbon sink even after building's end-of-life. As these materials are new in the market and no recorded data about its end-of-life is studied, LCA in researches assume landfill as the end-of-life choice for this material (Arrigoni et al., 2017).

3.2 Artificial carbon sequestered materials

Some recent studies have found potential in locking away the CO_2 from atmosphere into the building materials. This is either achieved by using the CO_2 supply from the CCS plants, atmosphere directly or the source of carbon emissions. The carbon emissions from most of the sectors in the Netherlands is taxed and the CO_2 supply from CCS plants is also charged. This leads the new researches to focus more on capturing CO_2 at the source site to be used in production of the building materials (Huijgen, 2003; Sanna et al., 2014; Turnau et al., 2019).

Although such companies/ researchers have a common goal, their technologies and products are different from each other. The products manufactured can broadly be divided into 3 categories based on the process involved in reducing the carbon emissions.

3.2.1 Replacing cement with SCMs (Supplementary cementitious materials)

The cement production alone in concrete industry is responsible for around 5-7% carbon emissions all across the globe (Ghoshal & Zeman, 2010a; Linden, 2017). At the same time, concrete serves as an essential material in the building industry. Hence, replacing concrete with an alternate material is still a long way from reality.

Many studies have investigated the possibility of using other substances to replace Ordinary Portland Cement (OPC) in the concrete production. The substances that have shown compatibility are known as Supplementary cementitious materials (SCMs). Fly ash, steel slag and silica fume are some examples of SCMs. Besides reducing the percentage mass of OPC in concrete, some SCMs also show potential in increasing the strength and durability of concrete (Souto-Martinez, Arehart, & Srubar, 2018; Yang, Jung, Cho, & Tae, 2014).

Different SCMs exhibit different properties in concrete, however, all of them have shown to reduce the carbon footprint of concrete as their percentage share in concrete is increased (typically between 10-50%). A research done by Ghouleh, Guthrie, & Shao (2017) studied the impact of using steel slag in concrete production, and claims that the concrete block thus manufactured by the process is carbon-negative.

Van Nieuwpoort Groep, a concrete manufacturing company has introduced variants of concrete mortar- Plus groen beton. These use recycled material such as granulated concrete and blast furnace slag as aggregates to lower the carbon footprint of resulting product (Van Nieuwpoort Groep, n.d.).

3.2.2 Carbonated curing of concrete

This process involves using captured CO_2 from the industry flue gas, in curing process of concrete. Studies have shown that this process of capturing CO_2 is not economical with the current technologies (Ghoshal & Zeman, 2010b). With the process of concrete carbonation curing, the concrete tends to form calcium carbonate ($CaCO_3$) particles inside itself imparting additional strength (Carboncure, n.d.; Kools, 2018).

Companies such as Carbicrete and Carboncure have been involved in using such production methods to reduce the overall environmental impact of concrete. Carbicrete team from Montreal has developed a technology that can be applied to precast concrete production industries. It uses steel slag as an alternative for cement and carbon dioxide during the curing process to sequester carbon in the end product. A standard sized concrete block thus produced is declared as a carbon-negative product sequestering 1kg and avoiding 2kg of CO_2. Their compression tests also prove that they have a compressive strength of 35.9 MPa, qualifying them to be used as a regular concrete block (Carbicrete, n.d.; Kools, 2018).

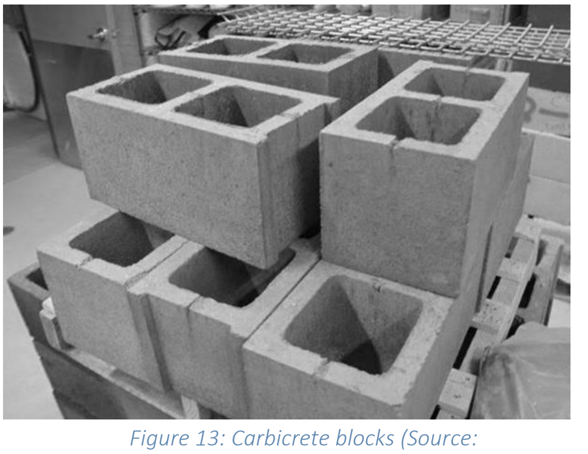


Figure 13: Carbicrete blocks (Source: http://carbicrete.com/technology/)

The Carboncure technology was developed in 2007 and several concrete manufacturing companies are now adopting their method to produce concrete. Their technology reduces the content of cement by using CO_2 at curing stage, lowering as much as 15kg of carbon emissions in 1 cubic meter of concrete block. The technology is available in either ready-mix concrete mixture or precast concrete blocks, however the impact of precast blocks on overall carbon footprint is much lesser than the in-situ concrete (Carboncure, n.d.; Kools, 2018).

The largest project where Thomas concrete company has applied this technology in concrete manufacturing has been built in Atlanta, Georgia (Figure 14). In this project, use of around 37,000 cubic meter has been said to sequester 380 tonnes of carbon dioxide from the atmosphere (Carboncure, 2018).

Figure 14: Carboncure technology used in a completed projected in Atlanta, Georgia (Source: https://www.carboncure.com/case-studies/2018/5/26/725-ponce)

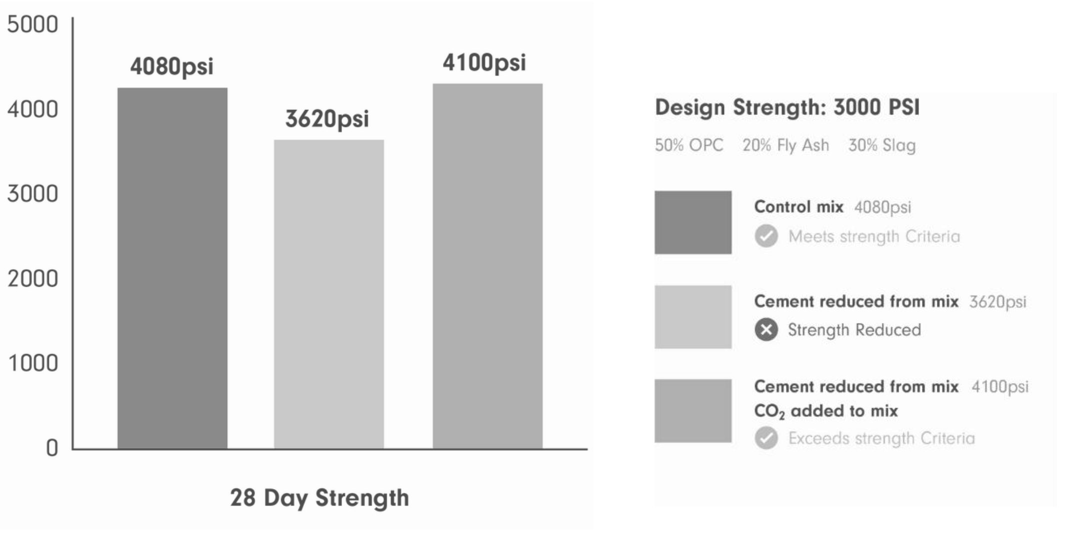


Figure 15: Carboncure concrete with different proportions of materials showing different compressive strength (Carboncure, n.d.; Kools, 2018)

3.2.3 Carbonated aggregates used in concrete

Besides cement, aggregate is another material used in enormous quantities in the production process of concrete. Concrete contains around 75% of aggregate, which makes aggregate as another potential material to store CO_2 and lock away in the concrete. Companies such as Blue planet and Carbon8 are involved in developing technologies that sequesters CO_2 in aggregates.

Blue planet, a US-based company and founded in 2012 has developed a technology to form carbonated rocks ($CaCO_3$) by sequestering CO_2. They manufacture aggregates that are available in different shapes and sizes and can replace the conventional aggregate materials (Blue Planet, n.d.; Kools, 2018). Their aggregate has been used commercially in the construction of San Francisco Airport in 2016. Figure 16 shows the in-situ concrete casting at site.

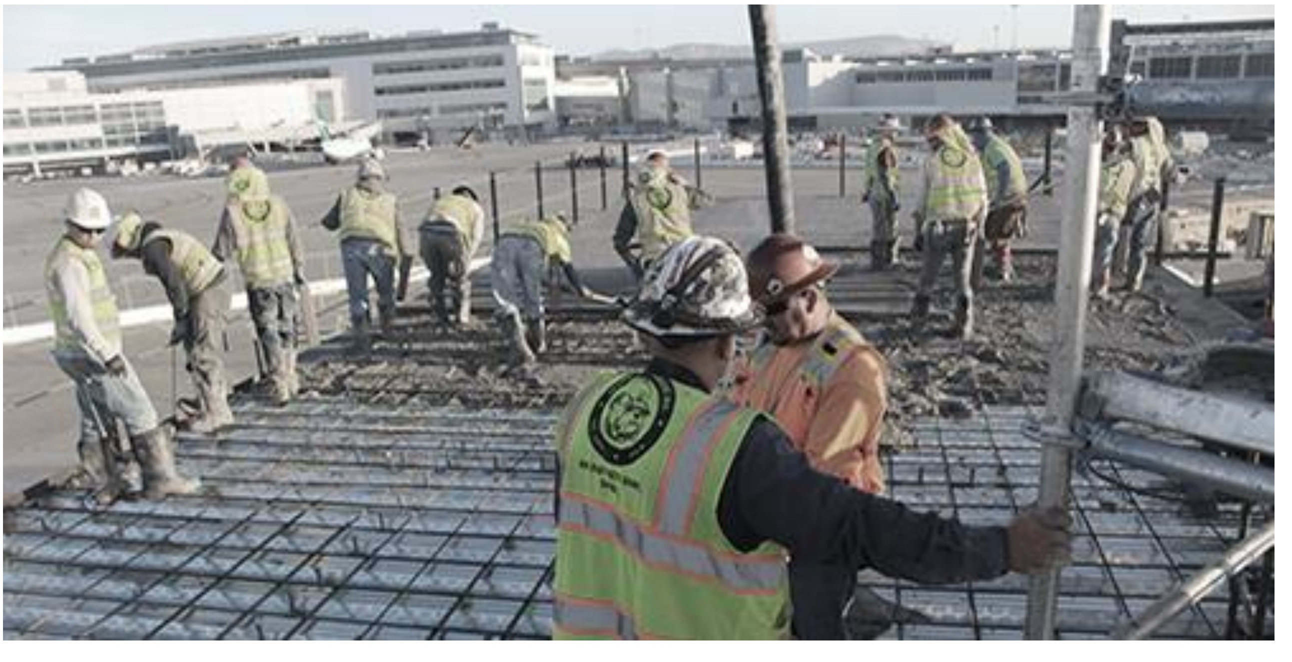


Figure 16: Use of Blue planet aggregates in concrete at San Francisco Airport construction site (Source: https://www.sustainablesv.org)

3.2.4 Comparison of artificial carbon sequestered materials

A study by Kools (2018) compares both the environmental and economic impact of the materials discussed above. The same is summarized and shown in Table 1. The products are comparable to other concrete solutions available in market and have similar lifespan and end-of-line scenarios. The CO_2 sequestered in the materials are converted into minerals that do not escape as carbon emissions even after demolition.

Another research by Turnau et al. (2019) indicates that such technologies usually demand more energy and raw materials associated in the process. Such processes are also dependant on the local available resources, such as renewable energy and waste heat cascaded from other sources. It does recognize the potential of using CO_2 at the carbon source and especially for concrete curing. The materials are further assessed in Chapter 06 |, based on common parameters.

Method	*Environmental impact*	*Economic feasibility*
Blue Planet aggregates	−	−
CarbiCrete blocks	+	+
Steel slag aggregates	+	+
CarbonCure concrete	+/−	+

Table 1: Comparison of Environmental and Economic impacts from the artificial carbon sequestering materials studied (Kools, 2018)

3.3 Summary

In this chapter, both conventional and unconventional building materials having low carbon footprint were studied. Conventional bio-based materials are seen to have several applications across the building. The use of engineered methods on such materials have allowed them to be structurally equivalent to materials like concrete and steel. Other developing bio-based materials such as hempcrete are seen to have limited application in construction.

Concrete has been used widely across the world for its cost efficiency and structural properties. This limits the possibility of completely replacing concrete with other materials. Therefore, solutions related to artificial carbon sequestration ***in concrete have emerged to lower its carbon footprint.*** Some methods such as replacing cement with other materials, carbon curing, and the use of carbonated aggregates in concrete are researched in many countries.

From the market and literature research, ***both bio-based and artificially sequestered building materials show potential to lower the carbon emissions***. The materials presented in this chapter were shortlisted from all those found on web. Some more companies/institutions developing materials that sequester carbon are TU Dresden, Calera, and MIT. However, due to limited data available in researches or websites, these materials were not studied further.

The materials presented in this chapter are mostly available for a large-scale application in buildings. Most of these materials are from US-based companies due to the lack of literature available for other local materials in English language. However, EPDs of local materials in different countries of European Union were also studied and similar materials were also found to exist in EU. Section 6.2 reports the data of such materials from EPDs or other available literature. Table 2 summarizes the materials discussed in this chapter along with their application in construction.

Materials to be analysed	Commercial-level implementation	LCI/EPD	Application in construction
Bio-based			
Wood			
1. Glulam and LVL	✓	✓	Light structural elements
2. OSB and MDF	✓	✓	Panelling and insulation
3. CLT	✓	✓	Heavy structural elements
4. SIPS	✓	✗	Insulation
Bamboo			
1. Ply bamboo	✓	✓	Light structure/ panelling
2. High density bamboo	✓	✓	Heavy structural elements
3. Flattened bamboo	✓	✓	Cladding
Hempcrete			
1. Cast-in-situ	✓	✓	Insulation infill material
2. Blocks	✓	✗	Light structure/ infill material
Artificially sequestered			
1. Replacing cement with SCMs	✓	✓	Concrete structure
2. Carbonated curing of concrete	✓	✗	Concrete structure
3. Carbonated aggregates used in concrete	✓	✗	Concrete structure

Table 2: Summary of materials with their application (Source: Author)

04 | Life Cycle Assessment

Life Cycle Assessment (LCA) is a method to assess the environmental impact of a product or a service. It uses the Life Cycle Inventories (LCI) of smaller units to calculate the impact on a specific indicator. These indicators are categorised on their potential impacts on the surroundings. Below are some commonly used indicators in LCAs (Bruce-Hyrkäs, 2018):

- **Global Warming Potential** (GHGs) (measured in kgCO_2 eq): All Greenhouse gases that have the heat trapping potential (Global warming potential) are represented in equivalents of CO_2 emissions. It is a relative measure of heat trapped in the gas. The period for assessment is assumed to be 100 years considering the atmospheric reactivity and stabilisation of the gases.
- **Acidification Potential** (measured in kgSO_2 eq): Certain acid forming substances released in the atmosphere gets deposited on the soil or water and deplete them. Such emissions are measured in kgSO_2 equivalent.
- **Eutrophication potential** (measured in kgPO_4 -eq): It is used to measure the Nitrogen, potassium or other organic emissions that can pollute to aquatic ecosystem.
- **Ozone depletion potential** (kgCFC_{11} eq): It is a relative measure of the potential of a gas to deplete the ozone layer as compared to Chloroflluorocarbon-11.

The materials used in a building goes through four major life stages, i.e. production, installation, operation, and demolition. In all these stages, consumption of resources and emission of substances have an impact on the ecosystem. LCA provides us with relevant information for a specific indicator to analyse the manufacturing process, installation methods, or choice of products. It can be used as a design tool to (Bruce-Hyrkäs, 2018; Melton, 2013)-

- Conduct a *whole-building life cycle assessment* for several design options and evaluate them on specific indicators. This is usually done at a later stage in design when the architects have the list of materials. However, evaluation done at an early design stage can yield better results.
- Assess a *single-impact indicator* and identify the critical design problems in a building. The same can be used to compare materials or certain distinctive design details.
- *Calculate the environmental burden* of a technology and its offset time, if required.
- *Achieve LEED, BREEAM or equivalent credits*

4.1 Variants of Life Cycle Assessment

International Standards Organization (ISO) has provided standards in ISO 14000 series to conduct LCA. There are 4 standards ranging from ISO 14040 to ISO 14043 that elaborates precise definitions, methods and requirements related to LCA (Bayer et al. , 2010; Peñaloza, 2017). The assessment method described by these standards are further discussed in Section 4.3.

The LCA can be divided into two types of variants depending on number of processing stages included for a product. One of the two LCA variant is chosen based on the purpose of assessment. They are known as Process-based LCA and Input-Output based LCA (Bayer et al., 2010; Schwarz & Weiss, 2017).

a. Process-based LCA

In this method, the bigger process is divided into part processes. The Life Cycle Inventory (LCI) data of such part processes are generally available in certain databases. In building industry, LCI of over a thousand materials can be found on databases available online. The data of such materials can be combined for an analysis to achieve the desired results. To limit the scope of such assessment, the indirect impacts on processes and lowest environment impacting processes are often ignored. This leads to an incomplete assessment, but more user-friendly analysis that can be conducted even by an architect (Bayer et al., 2010; Schwarz & Weiss, 2017).

The 3 approaches to process-based LCA methods in building industry are (Bayer et al., 2010; Vogtlander, 2014):

Cradle-to-Grave: This approach to LCA assesses the building from manufacturing phase (or cradle) until the end-of-life phase (or grave). It includes intermediate phase of building use and maintenance. Most online tools available to conduct the whole building LCA use this method. This takes away the opportunity to explore circular solutions (Vogtlander, 2014).

Cradle-to-Gate: This assessment method describes part of a product's life cycle from production phase (or cradle) to the factory gate (or gate). This is practiced providing product certificates such as Environmental Product Declarations (EPD). The databases that are used for whole building assessment are a compilation of such product assessments (Bayer et al., 2010).

Cradle-to-Cradle: This method is an ideal-case scenario for cradle-to-grave method where the product in its end-of-life is completely recycled. The circular design concepts are applied to achieve this vision.

A few more steps that are sometimes necessary to complete an LCA are:

Gate-to-Gate: An assessment of a part process that adds between two processes to complete the chain.

Gate-to-Grave: This is also a form of gate-to-gate assessment but assesses specific end-of-life solutions such as landfilling, combustion, disposal, or demolishing.

b. Input-Output based LCA

This method is used to quantify the materials and energy as input, and emissions as output. It includes a comprehensive list of processes involved in impact assessment and is used by sector-wide industries. It aggregates all the processes and provides a bigger picture of the impact of sector. This method is not used in building industry as it is not suitable to investigate the critical impacts from a step involved (Bayer et al., 2010; Schwarz & Weiss, 2017).

c. Attributional LCA vs Consequential LCA

The two variants of LCA give rise to Attributional and Consequential LCA. Attributional LCA are conducted with specific scope and the output is given in equivalents of indicators. Thus, it provides a content-specific analysis of a process that is difficult to interpret in other indicators. It also performs analysis based on static data available from the resources that overlooks certain aspects such as time-dependant carbon emissions from forest. The assessment of Attributional LCA is useful to compare products and methods due to its restricted boundaries (Brander et al., 2008; Schwarz & Weiss, 2017)

However, this often leads to from contrasting opinions on the impacts from indirect process involved for a product. This is provided by Consequential LCA. It assesses the impact caused by a product over the environment in several aspects. Brander et al. (2008) states that consequential LCA is more relevant for policy makers to map the impacts of particular policy.

4.2 Phases of Life Cycle Assessment

The four phases of the LCA methodology as described in ISO 14040 are (Bayer et al., 2010):

a) Goal and scope definition: The boundaries of an LCA and impact to be studied, together form the scope of an LCA. The functional units are also chosen for assessment. For instance, an assessment of building can be done using per square meter impact of the product. This makes it easier to compare it with another product and its impact.
b) Life Cycle Inventory (LCI): The individual processes inside the assessment scope are analysed to allot input and output values to themselves. This includes resources consumed per functional unit and its impact in specific indicators. These results can be found in datasheets provided by organisations such as Ecoinvent.
c) Life Cycle Impact Assessment (LCIA): This step groups together all the impacts in their respective indicator category and calculate their total impact.
d) Interpretation: The values obtained from the assessment is then analysed in light of the objective of the study. These values can also be used to compare different materials and make an informed decision.

4.3 Standards for LCA and EPD

The European Committee for Standardisation (CEN) have developed standards to assess buildings as shown in Figure 17. The building is assessed in three stages of life- production and construction stage, operational stage, and demolition stage (Peñaloza, 2017).

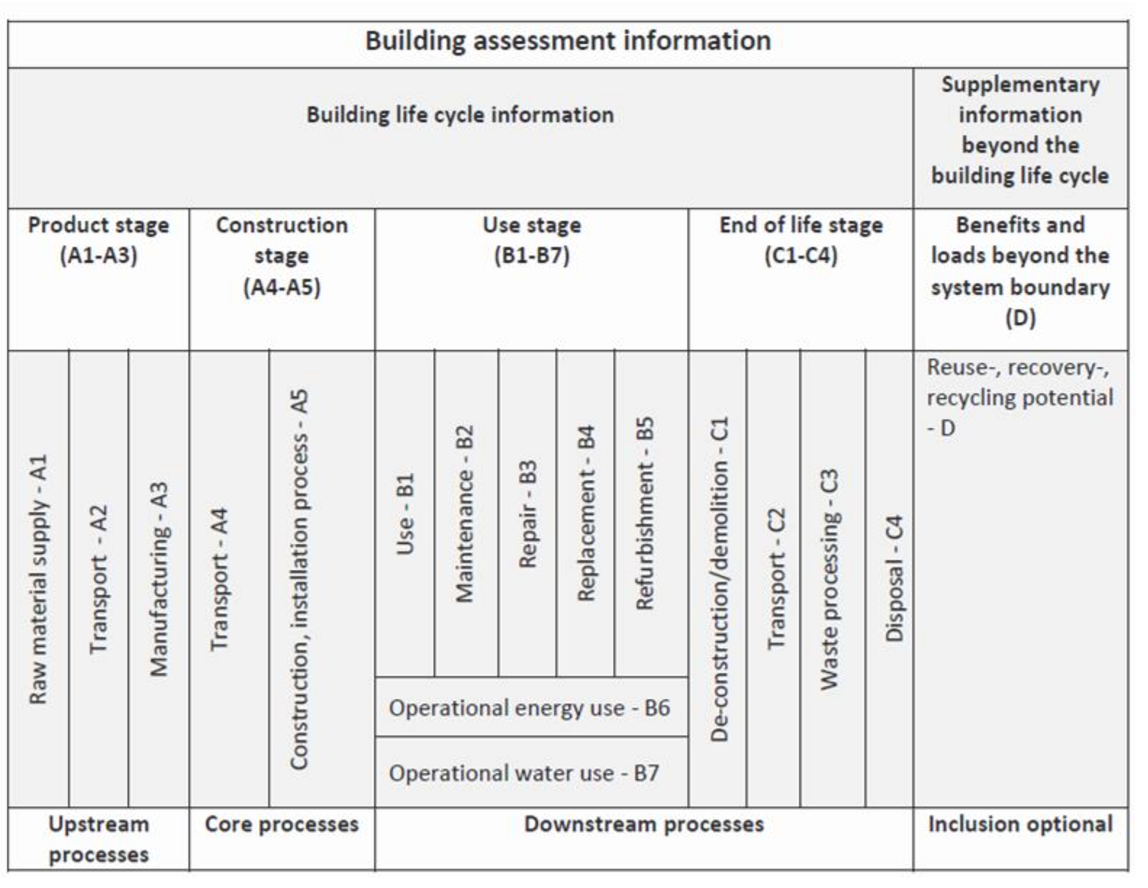


Figure 17: Life cycle assessment for a building defined by CEN. (CEN - European Committee for Standardization, 2012)

Figure 17 explains the different modules for a life cycle assessment of a building. These are:

Modules A1-A3(Product stage):

This module includes the carbon emissions resulting from all the processes involved in production of materials until they are ready to be transported from factory gate. They are usually declared by the manufacturer themselves as it can become difficult to calculate actual carbon emissions for a third party without sufficient internal information.

Module A4 (Transportation from manufacturer to site):

The emissions resulting from this module consider the distance between manufacturer and site, transportation type and load of the materials. These are calculated automatically by One Click LCA software used in this analysis.

Module A5 (Construction and installation emissions):

The emissions calculated in this module mainly results from the construction activities such as construction of foundations and other on-site activities. Other emissions from wastage of materials on-site are also included in this module. Some product declarations provide this information, while in other situations, assumptions need to be made.

Module B1-B5 (Use Stage- Maintenance, Repair and Refurbishment):

This module includes the emissions associated with maintenance, repair, and replacement of building materials over the lifetime of the building. The analysis often considers replacement as the only option based on the service life declared in the EPD of products. Other maintenance related emissions are not usually available in product declarations or the software, therefore, they are not considered and assumed to be almost similar for different materials.

Module B6-B7 (Use Stage- Operational):

These modules include the carbon emissions resulting from the energy and water consumption over the lifetime of the building. Efficiently designed buildings have much lower carbon emissions in this module. Since these modules are not relevant for embodied carbon emissions from building materials, they are not considered in this report.

Module C1-C4 (End of life stage):

The emissions related to deconstruction or demolition, waste processing and disposal of materials at their end of life are allocated in these modules. Module C3: Waste processing is directly related to the module D: benefits occurring from the type of disposal. This module depends on the scenario considered by the LCA practitioner or designer. It is essential to consider this module in the assessment as the design details may get affected by the choice of scenario.

Module D (Benefits beyond the system boundary):

The end of life scenario used in module C3 (recycle/reuse/incineration/landfill) affects the benefits allocated to the material in this module. Currently, this module is only required to be declared separately and not included in the total calculation as it would be impossible to check the future design decisions. However, they are now gaining more importance and developing an incentive system based on such benefits are being discussed.

Ecolabels such as Environment Product Declaration (EPD) for products are also produced based on the ISO and EN standards that assess the product from A1-A3 stage. EPDs are Cradle-to-Gate LCAs that provide standard set of data useful for comparing materials and assessing the whole building (Bergman & Taylor, 2011; Peñaloza, 2017).

4.4 Software and Datasheets used for LCAs

As mentioned earlier, the software and datasheets used for buildings are developed from process-based LCA method and thus are attributional LCA. While datasheets such as the ones provided from Ecoinvent provide LCI, other software such as open LCA, One Click LCA and Simapro can provide both LCI for products and LCA for buildings (Schwarz & Weiss, 2017).

There are currently many software used to assess the building and report its footprint in terms of different indicators. They either use the LCI values provided from open databases or accept manual values that can be found in EPDs. To make the process and assessment more user-friendly among architects and designers, some software such as Tally and Impact are developed. These software provide information using the BIM model. A comparison of these software is shown in Table 3 (Hollberg & Ruth, 2016).

360optimi tool mentioned in the table is now reintroduced as One Click LCA and provides some options for optimizations. Therefore, the student license for One Click LCA was procured for assessment of building level footprint. The impact indicator to be used in One Click LCA is kg CO_2 eq. and data provided in BOQ of Echo building will be used to run the analysis. Besides One Click LCA, more datasheets and EPD are consulted to assess the building.

Type	Name	3D model	Energy demand calculation	Embodied impact calculation	Optimization	Online / Offline	Country	Website
Generic LCA tools	Gabi			●		Off	Germany	www.gabi-software.com/software/
	SimaPro			●		Off	Netherlands	www.pre-sustainability.com/simapro
	OpenLCA			●		Off	Germany	www.openlca.org/
	Umberto			●		Off	Germany	www.umberto.de/en/
Spreadsheet-based tools	Envest 2*			●	○	On	UK	www.envest2.bre.co.uk/index.jsp
	SBS Building Sustainability		○	●		On	Germany	www.sbs-onlinetool.com
	Ökobilanz Bau		○	●		On	Germany	www.oekobilanz-bau.de/oekobilanz/
	eTOOL		○	●		On	Australia	www.etoolglobal.com/about-etoollcd/
	Athena Impact Estimator		○	●		Off	Canada	www.athenasmi.org/our-software-data/overview/
	Legep		●	●	○	Off	Germany	www.legep.de/
	Elodie		●	●		Off	France	www.elodie-cstb.fr/
	GreenCalc+			●		Off	Netherlands	www.greencalc.com/index.html
Component catalogues	EcoSoft			●		On	Austria	www.ibo.at/en/ecosoft.htm
	Bauteilkatalog			●		On	Switzerland	www.bauteilkatalog.ch/ch/de/Bauteilkatalog.asp
	eLCA		○	●		On	Germany	www.bauteileditor.de/
	BEES			●		On	US	www.nist.gov/el/economics/BEESSoftware.cfm
CAD integrated	Impact	●	○	●		On	UK	www.impactwba.com/index.jsp
	Cocon-BIM	○	●	●		Off	France	www.eosphere.fr/
	Lesoai	○	●	●		Off	Switzerland	www.lesosai.com/de/index.cfm
	360optimi	●	●	●		Off	Finland	www.360optimi.com/en/home
	Tally	●	○	●		Off	US	www.choosetally.com/

○ Partial functionality / additional software needed / external calculation
● Full functionality

Table 3: Comparison of different datasheets and software to assess buildings (Hollberg & Ruth, 2016)

4.5 Challenges and Limitations of LCA

LCA is known in building industry to assess the environmental impacts of building materials, construction method or to set benchmarks. It much depends on the LCI data supplied in the analysis and therefore, must be appropriately verified. Some challenges and limitations associated with LCAs are listed below (Bayer et al., 2010; Building Green, 2013; Melton, 2013; Schwarz & Weiss, 2017).

- Appropriate LCI's are dependent on carefully assessed products. EPDs can serve as reliable source but the scope must still be checked and reported.
- As different fields of science are involved in reporting data that collectively produce LCI, the consistency of analysis is often uncertain.
- LCA can be used as a tool to comparing materials and interpret their impacts. However, assuming a material is completely sustainable or carbon neutral from an LCA would not be a correct use of LCA.
- LCA can only calculate the environmental burden measured in equivalents of emissions, and not the social or economic impacts associated with the product's life.
- The static nature of life cycle where the dynamic constraints such as time are not accounted, is identified as a major limitation of LCA software.
- Misinterpretation of results from EPD and LCA is a common problem in building assessment. For instance, a material may be unsustainable choice in one application and sustainable in another, as compared to another material.
- The recycling choice in Cradle-to-Gate method does not clearly evaluate the resources needed to recycle a product. For instance, a circular solution which can be recycled is hard to differ from the solutions that can be recycled but with a lot of resources.

4.6 Summary

The life cycle assessment (LCA) method has been elaborated in the chapter highlighting its application in buildings. The method serves as a suitable option to compare materials or create benchmarks. These are also used to achieve credits in green labels of buildings. However, there are still many challenges with the assessment method. Several researches are studying alternate methods to overcome these challenges related to carbon counting beyond the life of building or benefits of circularity. These researches sometimes conflict with each other and thus, ***do not have a clearly defined assessment method yet.***

ISO standards and software approved by councils have been studied and reported in this chapter. It is widely accepted that these standards must be used to assess the buildings to make environment-friendly decisions, and not to establish claims such as zero carbon design. Thus, for further analysis, such software and EPDs are used along with careful interpretation of recycling and cross-sectoral impacts of the materials. In the next chapter, an assessment method is defined with careful adaptations in existing method. Pre-defined EPD data for common materials would be used and compared with literature-found data of unconventional materials. Wherever possible, default input provided by the One Click LCA tool would be cross-checked with literature findings. The remaining gaps in information would be duly reported to present transparent results. The assessment strategy thus formed would be used to compare building materials.

05 | Defining assessment method

5.1 Echo building data reporting

Echo is a new building in TU Delft campus, currently in design detail and construction phase. It has a planned Gross Floor Area of 8300m^2 and set to be functional from 2022. It will accommodate an auditorium, few restaurants, and many classrooms. The building is planned to be a net-positive building with emphasis on material selection to bring down the carbon footprint of the building too.

The data obtained from the Campus and Real Estate (CRE) department, TU Delft is reported below. It indicates most of the structure is designed in steel and partly in concrete. For wall panelling, interior decoration and acoustic ceiling, bamboo slats are used. Table 4 shows more materials and their application in the construction.

Figure 18: A night render of Echo building (Source: Confidential report)

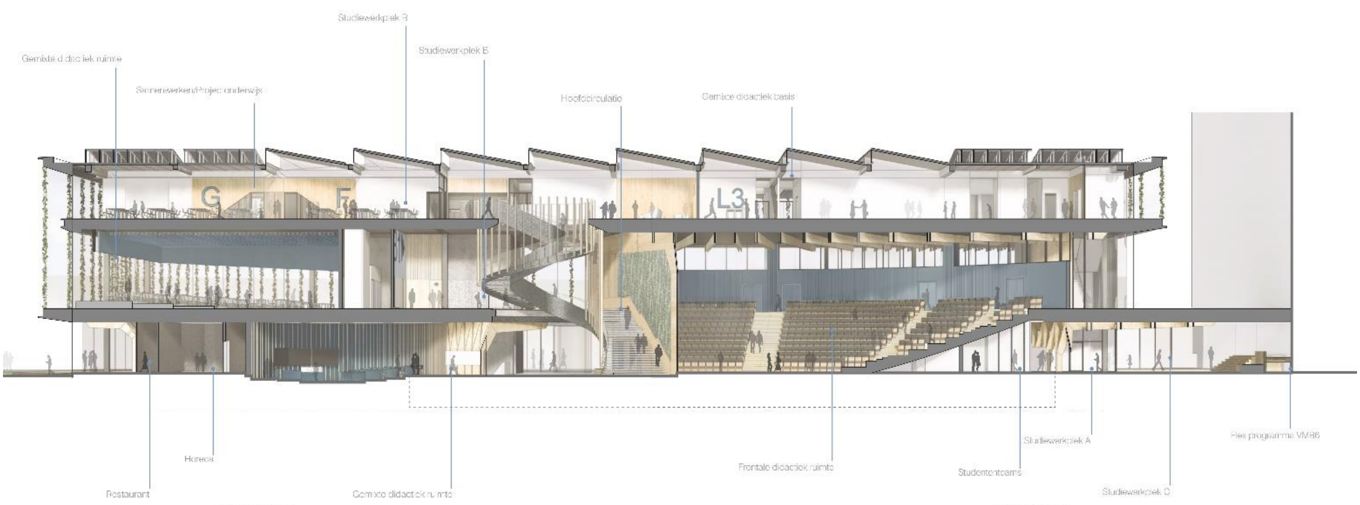


Figure 19: Organization of spaces shown in the section of the building (Source: Confidential report)

Materials used	Application in construction
Concrete	Structure
Steel	Structure
Bamboo slats Wood/ flattened Bamboo	Ceiling panels Structural framing Flooring
Concrete finish	Floor finish
Glass and Aluminium	Façade
Vinyl	Wall finish
Linoleum	Floor finish
Felt baffles	Acoustic ceiling

Table 4: Materials used in the Echo building (Source: Author)

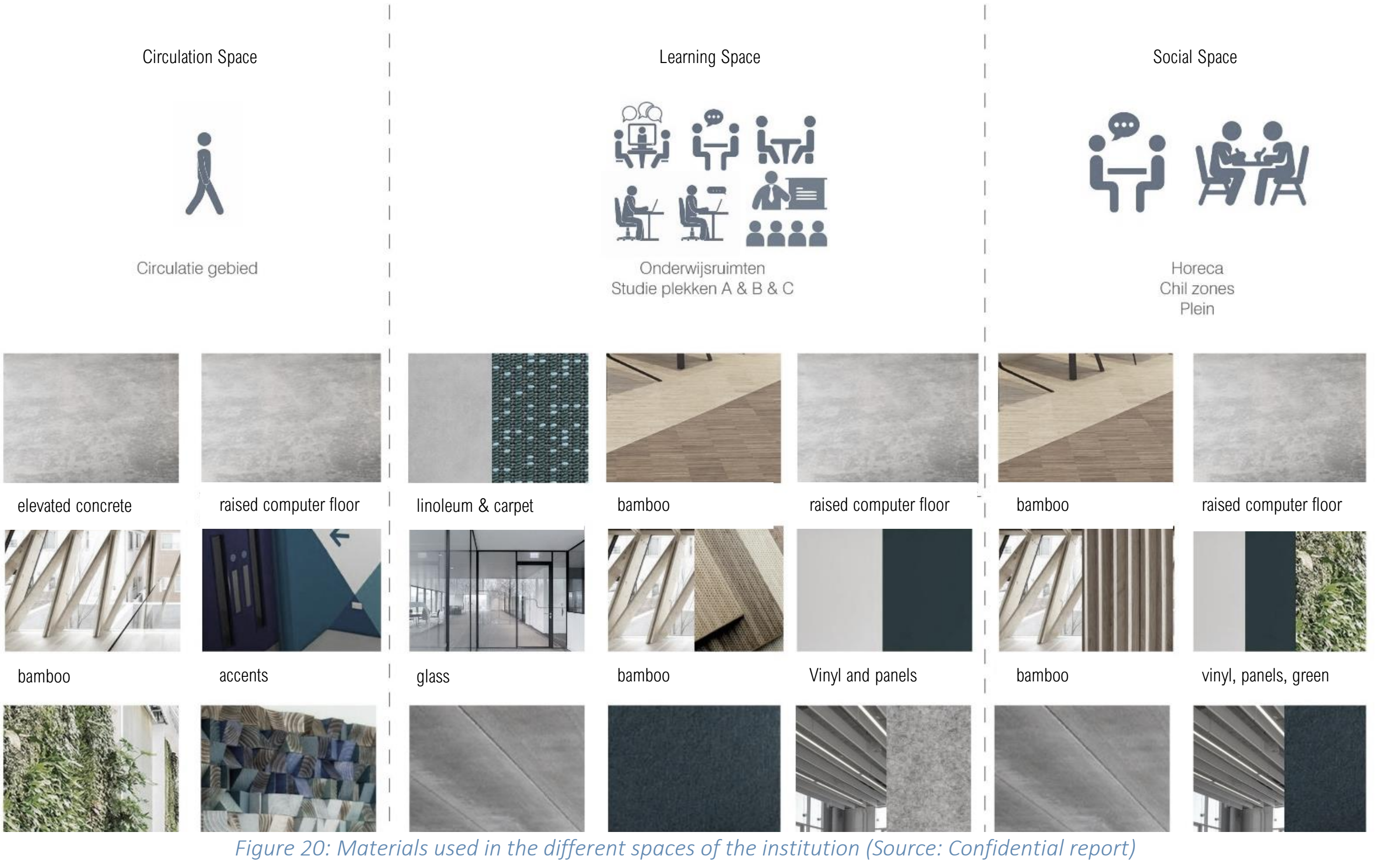


Figure 20: Materials used in the different spaces of the institution (Source: Confidential report)

Chapter 6 further discusses the building elements chosen for assessment. The quantities obtained from the information provided by the architects is used to estimate other alternate material quantities. The construction details are also studied to check the feasibility of proposed solutions.

5.2 Challenges with current assessment methods

As EPDs provide material information verified by a third-party organization, they serve as a reliable information source. Usually architects are not involved in these calculations, therefore, easy-to-use tools not developed to provide estimated results for their design. This may benefit the design to some extent; however, they may lead to unsustainable choices if misused. Thus, interpretations of LCA results are a crucial part of assessment.

To simplify the assessment method for non-LCA practitioners, certain aspects of LCA are either neglected or set to default in the available tools. Besides these aspects, there are some more limitations to using LCA. This is because new strategies such as circular design were developed after the standardization of LCA in 1990s (Guinée et al., 2011). The conventional assessment method to compare materials have following limitations that are often overlooked by carbon designers.

a. Material quantities

It is well-established that primary energy used in the production of steel is much higher than the concrete and wood. This leads to a higher carbon footprint of steel if compared directly using kg CO_2 equivalent/ m^3 of material. However, it must be noted that the structural performance of the materials requires them to be used in different quantities for a specific sized structural member. Figure 21 shows the difference in material quantities needed for a beam of 13m span. The impact on carbon emissions can be seen to reduce drastically bringing the 3 material options in a comparable range.

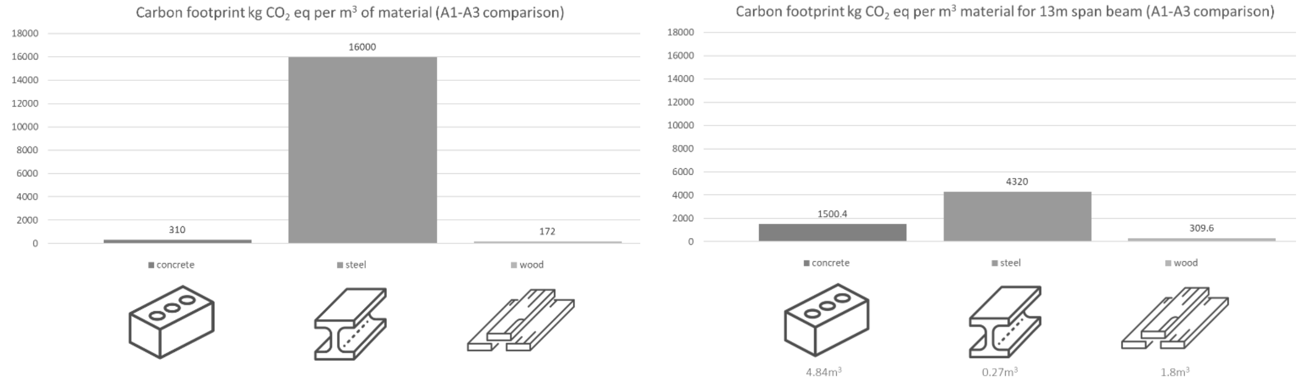


Figure 21: Comparison of module A carbon emissions between concrete, wood, and steel (Source: Author)

Thus, for the assessment of Echo building, material quantities with equivalent structural performance were needed. This would serve as an input to the One Click LCA tool for calculations. The results obtained from this would still not be comprehensive due to factors that are explained in next points.

b. Accounting module D benefits

Simplification of the life cycle assessment led the standards such as EN 15978 to make the scope D module optional. It was done to avoid double-counting the benefits of recycling the materials. In other words, primary production of a material using recycled ingredients already declare this information in Module A carbon emissions. If the same recycling potential of material is assumed for its end of life, adding this benefit again in the calculation would lead to double counting.

This takes away the opportunity from architects and designers to think beyond recycling materials. Reusing the material would further reduce the carbon emissions from whole life cycle impact and therefore, would contribute as an important part of assessment. Some recent studies are using different approaches to include Module D benefits. The assessment method thus proposed in next section would also address this challenge to present results as precisely as possible.

c. Misinterpretation of LCA results or EPDs

Due to abovementioned reasons, EPDs are commonly misinterpret. It is sometimes due to the lack of information declared in the EPD or just wrongly interpret information. Few organizations such as the Institut Bauen und Umwelt e. V. (IBU) provide an EPD with carefully elaborated Module D for a material. This report makes use of such EPD data as much as possible.

The LCA practitioners often interpret the results in the way that suits their needs. On the other hand, the whole building LCA cannot be done precisely due to the complexity involved. Thus, false claims of designing a completely zero carbon building need to be avoided. If anything, the results should be used to guide the designs through different scenarios.

5.3 Framework and scope of analysis

The analysis in this report considers the whole life cycle of a material as a building element in a construction. As explained earlier in section 4.3, CEN TC350 standards uses modules from A-D with further divisions to cover each life cycle stage of a product/ building. This report uses the same methodology to report the results. Module B6 and B7 are not considered as they do not affect the embodied carbon emissions of a material.

Module D generally reports the benefit of end-of-life scenario of a material. In a realistic scenario, module D is often a combination of two or more processes, such as steel is partly reused and partly recycled. To highlight impacts from different end-of-life situations, this analysis considers 100% of each scenario to occur.

Product Stage			Construction Process Stage		Use Stage							End-of-Life Stage				Benefits and loads beyond the system boundary		
Raw material supply	Transport	Manufacturing	Transport to building site	Installation into building	Use/application	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction/demolition	Transport	Waste processing	Disposal	Reuse	Recovery	Recycling
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D	D	D
X			x	x	x					MND		x				x		

Table 5: Modules considered for the assessment (X- considered, MND- module not declared) (Source: Author)

Another important adaptation introduced in the assessment method is consideration of 2 life cycles of a building with a lifetime of 60 years (or 1 life cycle of a building with 120 years). Figure 22 explains the scenarios considered for two buildings with different lifetime, i.e. 120 years and 60 years. The life cycle for 120-year-old building is quite straight forward with options only for its end-of-life (energy recovery/ recycle/ landfill). However, the building with 60 years life first has a choice to either be demolished or disassembled, and allow its materials to be recycled or reused respectively, for the next building with lifetime of 60 years. This would allow for the accounting of recycling benefits from both module A and C. It would also help in comparing the carbon emissions of a new construction to a long-lived building with mid-life renovations.

The life expectancy of structural building elements was assumed to be 120 years, based on the literature and market study. Other building elements analysed are assumed to have lower life span, based on the indicated years in One Click LCA tool. The scenarios were thus built using the two options of life span, i.e., 120 years and 60 years.

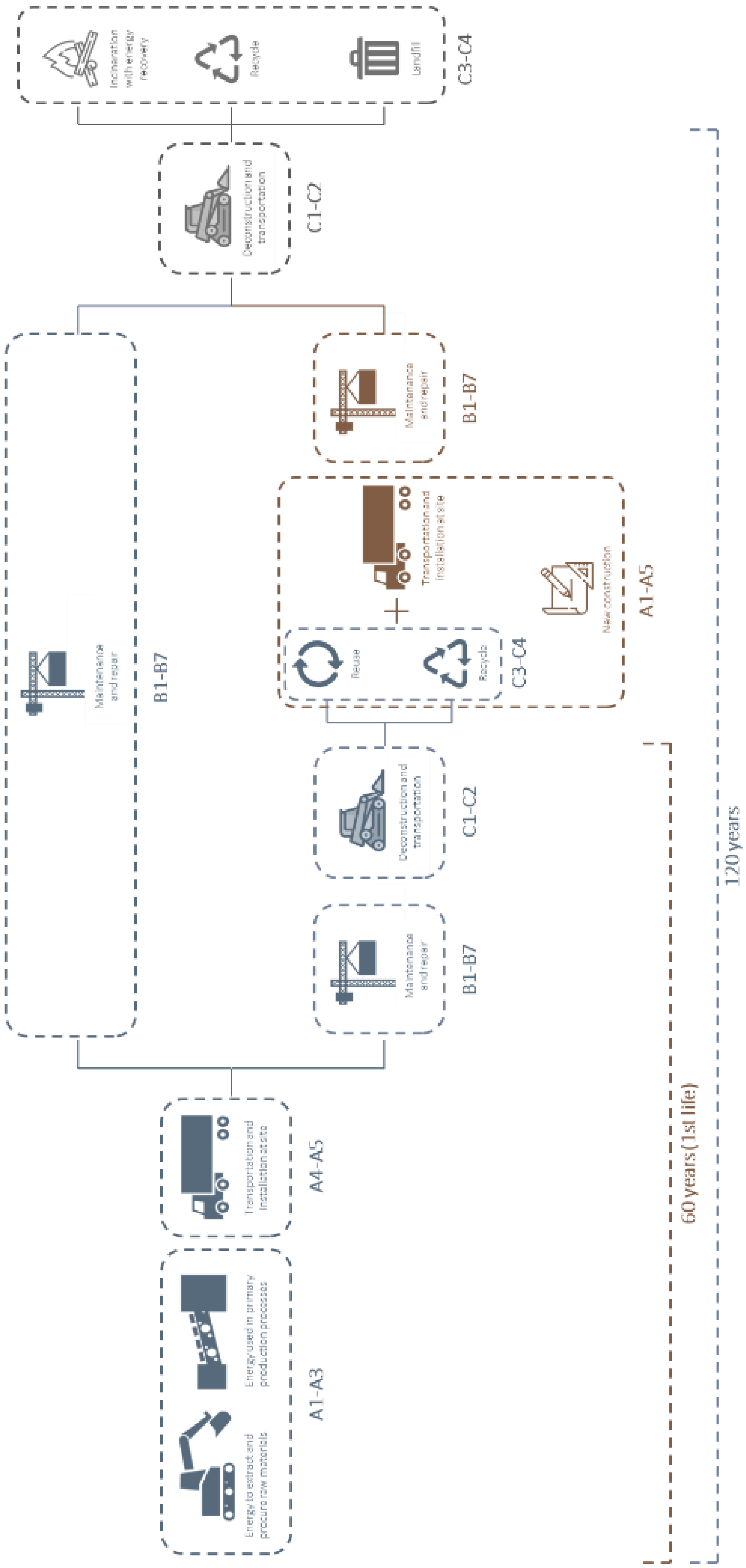


Figure 22: Life cycle considered for the assessment method (Source: Author)

5.4 Scenarios

The life cycle scenario for each case as explained in Figure 22 is given a code using some parameters. This is done to present the results for a building element in an organized format for different material options, each with several life scenarios. The code is derived from:

$$Code: (Lifetime\ of\ building)_{(EOL\ 1)_{EOL\ 2}}$$

Where:

Lifetime of building could either be 120 years or 60 years

EOL (End-of-life) could be Incineration (I), Recycle (RC), Reuse (RU) or Landfill (L)

As an example, for a building scenario of 120 years lifetime and Landfill of material at EOL, the code would be 120_L. Other example for a building with first life of 60 years and disassembled to allow is structure to be reused for a second life of 60 years again and finally be demolished for incineration, the code would be 60_RU_I (Appendix 12.2).

5.5 Considerations for the assessment method

The assessment method is guided by several parameters involved in the LCA. While each factor influences the analysis, some have a greater impact than the other. It is important to note that the LCA method is still evolving to provide more and more accurate results. Therefore, the values and assumptions used in this report also intend to provide a theoretical case of comparing materials.

a. One Click LCA and its parameters

One Click LCA software has a vast database of EPDs from different parts of the world. It can either be integrated with software such as Revit, Design builder, ArchiCAD, etc, or it can take value-based inputs manually. The tool is capable of generating different type of outputs based on the requirement. It is primarily used in this report to quantify the Global warming potential (kg CO_2 equivalence) of different materials. This data is extracted for each module of LCA (A-D) and later used for interpretation.

The EPD database available in the platform is divided into 2 categories- generic data and specific data. Generic data is an industrial average of the database available for that specific material type. They are even distinguished by specific regions or countries to supply more accurate information. Specific data, however, are declared by the manufacturers and their third-party verifiers as EPD. Specific data provides much more accurate results and should therefore be used when the material suppliers are finalized. They can also be used to compare environmental impacts of material from two or more suppliers (One Click LCA, n.d.). Since the goal of this research is to have a broader perspective of materials and their impacts, generic data is preferred. This is done to avoid disparity of selecting the best or worst material option available in the market.

The material quantity and choice are entered in specific categories of building elements, such as foundation, façade, column, beam, etc. This is helpful while generating output based on the categories of building elements. The material quantity can be entered in any units (kg, m^2, m^3).

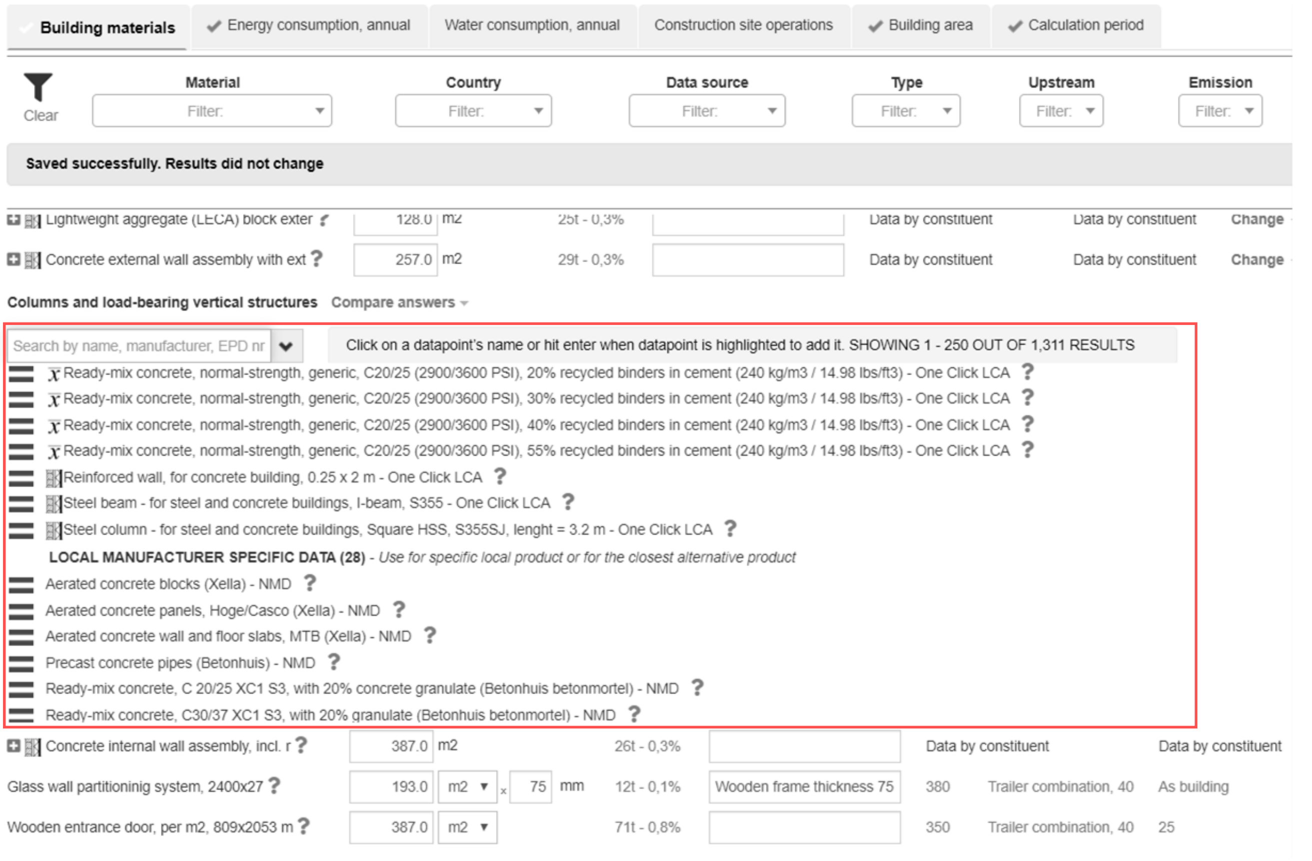


Figure 23: Generic and specific database example in One Click LCA (Source: Author)

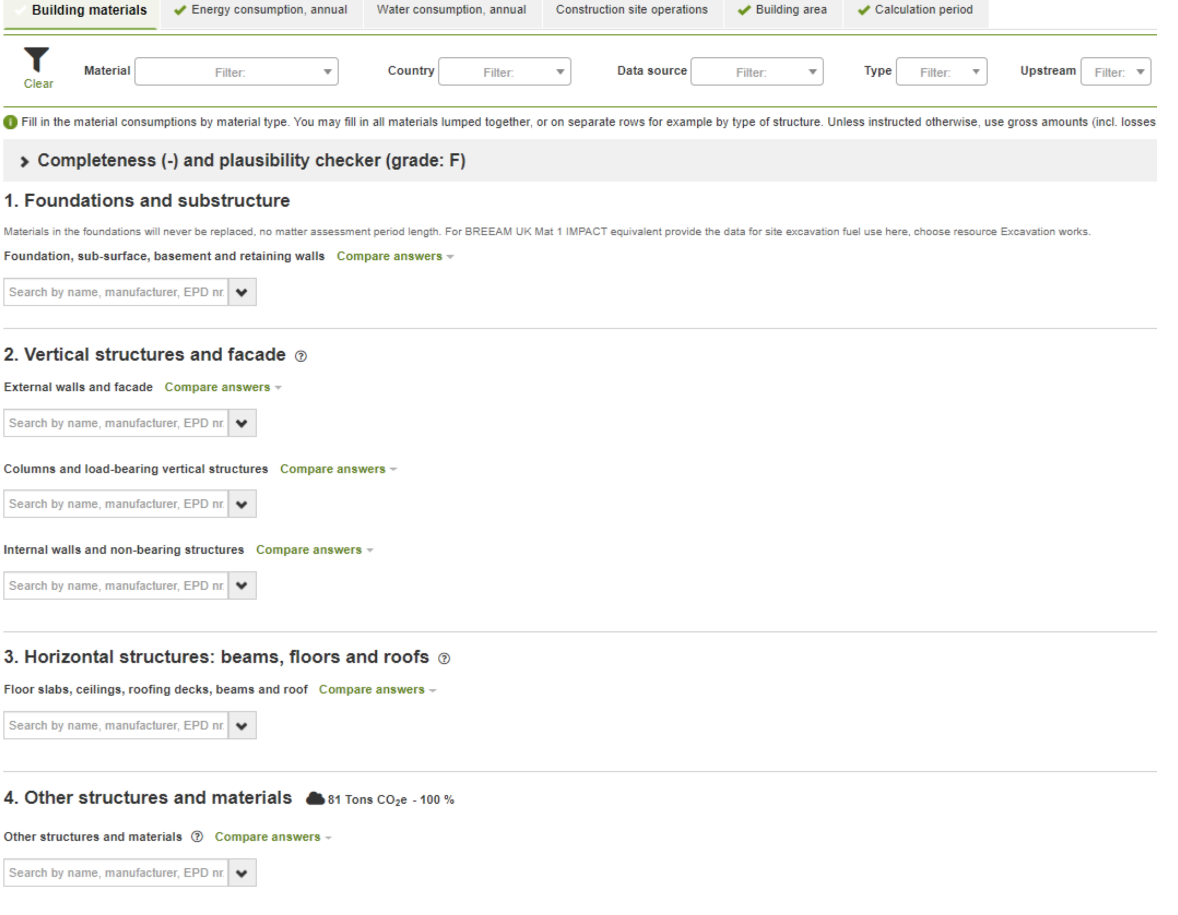


Figure 24: One Click LCA tool interface for adding building material and their quantities (Source: Author)

b. Determining material quantities

Using quantities of material that has equivalent structural performance is a crucial aspect of executing the analysis. As shown in Figure 21, material quantities drastically impact the results. Thus, a standard thumb rule to estimate these quantities had to be established. Columns, beams and slabs were the basic structural elements studied for the assessment and material options of concrete, steel and wood were considered. To establish a relationship between the quantities of these materials, 3 sources of information were looked at.

1. Karamba3D tool in grasshopper
2. Carbon Designer tool in One Click LCA
3. Manual for determination of dimensions of floor, beams, and columns by Dr.ir. W.J. Raven

Grasshopper script using Karamba3D tool was developed with material type and dimension of structural element as input (Appendix 12.1). Same support and load conditions were applied to all the cases and the maximum deflection in beams, columns and slabs were checked (Figure 25). As the most common beam span in the Echo building is 13m, the analysis in this script was set for 13m span. The cross-section type (hollow/ solid) and dimensions (width/height) were changed for different material options to achieve same deflection in the beam. Once the deflection was matched for different materials and their cross-sections, the mass and volume of material used for the structural member was noted.

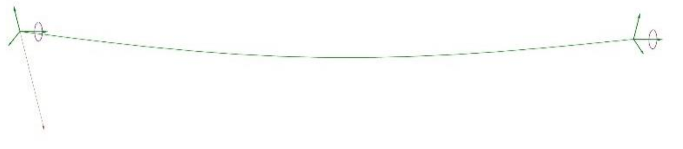


Figure 25: Deflection in beams represented as a line diagram by Karamba3D tool (Source: Author)

Carbon Designer tool in One Click LCA is a function that allows a user to optimize the design as simply as possible. It has some default material options for each building element to compare the results. For instance, by applying a scenario of wood to the design, the graphs show a comparison of existing design with an all-wood structural design. This function was used to gather quantities of material from the default values used in the software (Appendix 12.1).

Finally, a **Structural design manual** provided by Peter Eigenraam, was consulted for thumb rules to determine the size of beams, columns, and slabs in wood, steel, and concrete. The manual gives simple ratios between L (span), h (height) and b (width) of the cross section for the structural members in different materials. As an example, the ratio of h/L would be 1/20 for a wood beam, 1/25 for a steel beam or a range from 1/10 – 1/20 for a concrete beam.

These methods of determining structural quantities were used and verified with each other. However, to have a consistent source of information, values from carbon designer tool were used for the final analysis. Table 6 summarizes the required amount of materials for a beam with 13m and a column of 5m height. It also estimates a ratio of concrete and wood structural members to that of steel as structural design of the Echo building mostly contains steel sections. These ratios are later used in Chapter 6 to calculate the total amount of material options for the Echo building.

	Steel		Concrete (mortar)		Wood	
	Mass	Volume	Mass	Volume	Mass	Volume
Beam (13m span)	1,755 kg	0.22 m^3	10,687 kg	4.45 m^3	670 kg	1.39 m^3
				20 x volume of steel		**6.3 x** volume of steel
Column (5m high)	285 kg	0.04 m^3	1085 kg	0.45 m^3	168 kg	0.34 m^3
				12 x volume of steel		**8.5 x** volume of steel

Table 6: Mass and volume required for a specific structural member (Source: Author)

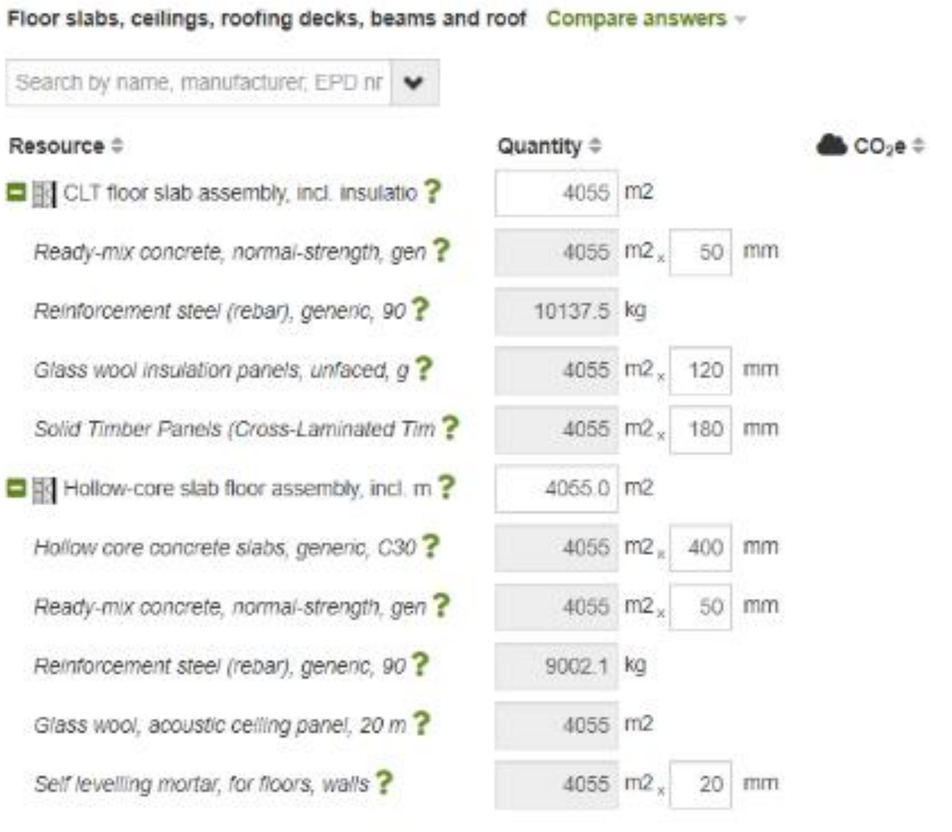


Figure 26: Material options of hollow concrete and wood provided by One Click LCA for slabs (Source: Author)

The assumption of slabs was slightly harder as compared to the beams or columns. The slabs also constitute other materials such as insulation. Therefore, to ease the calculation of material options for slab, default input provided by One Click LCA tool was used (Figure 26). The difference in slab thickness was automatically adjusted by the software as per the structural requirement.

Material quantities in mass and volume for other buildings elements (i.e. façade windows, façade awnings and insulation) was directly obtained from the EPDs. As the EPDs of these building elements use area of application as their declared units, it is relatively easier to calculate the mass and volume of materials.

c. End of life scenarios

The end-of-life scenarios considered in this assessment method includes landfilling, incineration, recycling and reusing. Much of the data available in literature and EPDs have consistent values for landfill and incineration (energy recovery) scenarios, sometimes even recycling. However, the concept of circularity and Design for Disassembly (DfD) is relatively newer concepts. The buildings currently being built with this principle have not yet reached its end-of-life and therefore, it is difficult to get practical values for energy required in disassembly of a structure. Due to limited literature available on this subject, theoretical values obtained from a research conducted by Athena Institute is used (Gordon Engineering, 1997).

The results from research of Gordon Engineering (1997) are also used in a technical report published by European Commission recently (Gervasio & Dimova, 2018). It analyses an office building to identify the energy used in demolition/ disassembly at its end-of-life. Although the research was conducted in 1997, its methodology considered the actual time of demolition of the building, i.e. 2046-2076. This allowed the analysis to use idealized values of processes to account for the improvements that have occurred over time.

	Frame to be recycled (in MJ/kg)	Frame to be reuse (in MJ/kg)
Steel frame	0.239	0.432
Concrete frame	0.070	0.061
Wood frame	0.323	0.176

Table 7: Energy used (in MJ/kg) for the demolition/deconstruction of different structural frames in buildings (Gervasio & Dimova, 2018)

Table 7 summarizes the results of the research. It entails the energy used on-site for disassembly/ demolition of the structure in three material options, i.e. wood, steel and concrete. However, these values did not take into account the transportation of materials to the storage and sorting facilities, or the energy required to run such sorting facilities. The value for transportation was estimated to be the same as initial transportation from production facility, based on the assumption that the same facility serves as a reuse centre for its product. Finally, the energy required to run the centres were not accounted, assuming similar time and energy would be spent on such process.

The conversion of demolition energy units (MJ/kg) to carbon emissions (kg CO_2/ kg of material) was achieved by using the standard carbon emission factors of fuels in the Netherlands (Vreuls, 2004). Since the earlier research assumed the energy values based on Gas/ Diesel oil, the same energy source is used to obtain a value of 74.3kg carbon emissions per GJ of energy.

d. Carbon sequestration potential

The materials studied in this report were earlier classified into two categories- biologically sequestered carbon materials and artificially sequestered carbon materials. The EPD of materials studied for the analysis has shown that the biogenic carbon in former category materials are usually reported in the declarations. The artificially sequestered carbon technologies have not yet been successfully reported in any EPD, but the EPDs of concrete products manufactured using SCMs are available. Their low carbon emissions in production phase is evident from the EPD due to lesser percentage of cement in the material.

Biologically sequestered carbon materials are shown both with and without the biogenic carbon in the life cycle. Although they do not change the result for a material, they do cause higher fluctuations in carbon cycle if taken into account. Besides the carbon sequestered in primary production, concrete products also sequester carbon dioxide when they are exposed as structural element in a building over its lifetime. This process is also known as carbonation that occurs between the hydrated cement of concrete and atmospheric carbon dioxide (Souto-Martinez et al., 2018). While this phenomenon was never accounted in the EPDs due to lack of information, only recent researches have been able to estimate values of carbon dioxide sequestered in different types of concrete. Concrete with SCMs require less amounts of Ordinary Portland Cement (OPC), thereby reducing the carbonation effect in such concrete (Souto-Martinez, Delesky, Foster, & Srubar, 2017; Yang et al., 2014).

Table 8 summarizes the results from research conducted by Souto-Martinez et al. (2018), showing the decreasing percentage of sequestered carbon in concrete products manufactured using SCMs. These values are later used in the analysis as benefits in carbon cycle for concrete products.

	% CO_2 recovered via carbonation
Finite exposure (25 Years)	
Normal OPC concrete	8.2%
10% Fly Ash	4.9%
20% Fly Ash	2.2%
10% Slag	6.1%
20% Slag	4.3%
Infinite exposure	
Normal OPC concrete	17%
10% Fly Ash	11.3%
20% Fly Ash	5.6%
10% Slag	14.0%
20% Slag	10.9%

Table 8: Percentage of carbon emissions recovered via carbonation in a concrete of 30MPa compressive using common cement. Adapted from (Souto-Martinez et al., 2018)

5.6 Uncertainty and variability in the method

A range of EPDs are available for each material, except for bamboo and hempcrete. For bamboo, EPD from only one company- Moso was found. Figure 27 shows the range of EPDs found for each material and the data used for the analysis based on the availability of comprehensive information. Since the data available from EPDs only provide module A emissions, the rest of the modules in LCA were analysed using available literature.

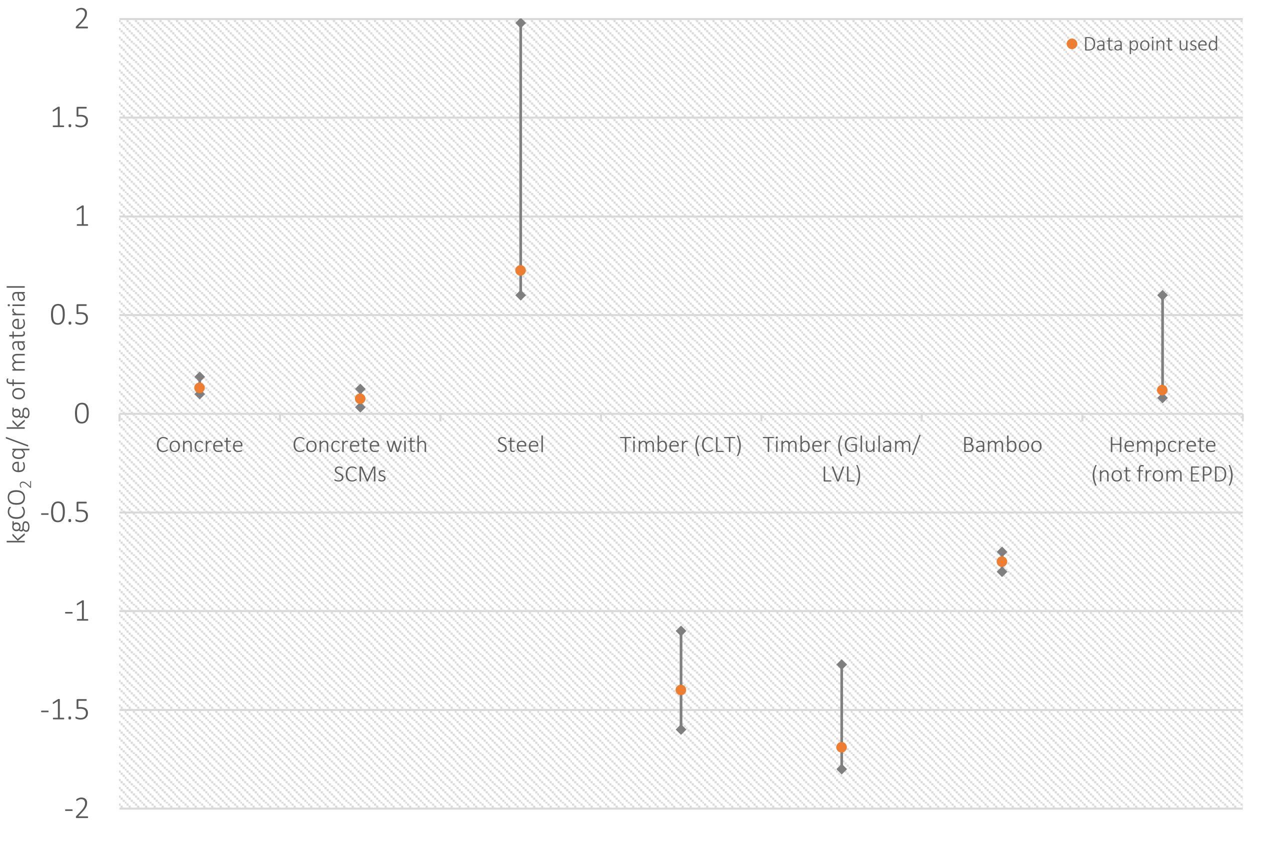


Figure 27: Carbon footprint kg CO2 eq. per kg of material (A1-A3 comparison) (Source: Author)

The excessive amounts of data being used in the LCA analysis makes it prone to errors. For this reason, iterative checks and comparison to existing LCA studies are recommended to achieve better results (Carbon Leadership Forum, 2019). Some of the following reasons may cause variation in results from the actual ones:

1. *Diverse literature sources:* The assessment method used in the report considers different scenarios for end-of-life. Since this information is not available in all the EPDs, diverse literature sources need to be consulted to gather data. As these data do not follow the same PCR (Product Category Rules), they might cause variation in the scope of assessment. To overcome this problem, a single literature data is used for all the similar calculations across different materials to maintain consistent boundaries. This is intended to achieve higher precision in results (Figure 28).

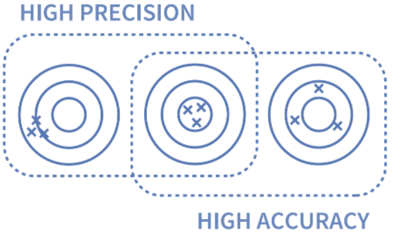


Figure 28: Figure explaining that accuracy is a check between the measured value and the actual value, while precision checks the measured values to each other (Carbon Leadership Forum, 2019)

2. *Ideal scenarios considered:* The analysis considers 100% of the end-of-life scenario for a particular material, whereas this is never the case in real practice. For instance, steel is recycled as much as possible, but 10-20% of it still goes to landfill in the Netherlands. Although it is done to highlight the impacts of different scenarios, they may not reflect the practical situation.

3. *Consequences of material alternative:* The use of alternate materials may cause a need for some specific solutions, such as fireproof coating for wood solutions. As this may cause more carbon emissions than the calculated results, careful interpretation must be done from the analysis.

4. *Life expectancy:* Based on the literature study, the life expectancy of certain materials is assumed to be a maximum of 120 years. However, there may be a possibility of even using/reusing them longer. This would further reduce their environmental impact. For instance, steel and concrete structural elements may be suitable for a longer life span, allowing them to reduce their environmental burden.

5. *Carbon neutrality from forests:* The wood material alternatives proposed in the report are assumed to be processed from sustainable forest management. This allows the analysis to consider carbon neutrality in the growth phase of timber. Importing wood from an otherwise scenario may put an environmental burden indirectly arising from the forests. The assumption of procuring wood from sustainable forests is based on the fact stated by NEN (2014) that all major European countries follow Kyoto Protocol for forests. Caution must be taken in case the wood is imported from other countries.

It is acknowledged that these factors may cause the results to be inaccurate. Therefore, a range of ±5% of the output would be considered acceptable for comparison to other materials for interpretation. For instance, carbon footprint of a wood column in scenario 120_RC is calculated to be 39.2 MtCO_2e; and that of a concrete (type-3) column in scenario 60_RU_RC as 37.3 MtCO_2e. Considering a range of ±5% for both the materials, they would both be assumed equally suitable while drawing up the conclusions. Finally, it must be noted that the results would provide precise comparison between carbon footprint of materials, but not the actual environmental impact of the building.

5.7 Summary

The comparison of materials for an application in building is more complicated than it may seem. Since the declared carbon emissions of materials in EPD are either per m^3 or per kg of materials, it cannot be directly used for comparison. Similarly, the EPD of materials often do not declare the end-of-life benefits. The irregularities in of such considerations ***may lead to wrong interpretation of results.***

A standardized approach to calculate the carbon emission of materials was proposed to ***assess them within similar scope and parameters.*** Some adaptations to the existing LCA method were proposed such as assessment of 2 life cycles of a building to include the shared end-of-life benefits (module D) of the building. The results from this method would also provide a comparison between a building with life span equal to 2 life cycles of another building. Another important adaptation to the assessment method proposed was to consider 100% of the end-of-life scenarios of materials. This would allow the results to highlight the impact of different end-of-life of materials and design accordingly. To simplify the documentation of analysis, the scenarios were named using a code: *(Lifetime of building) _ (EOL 1) _ (EOL 2),* such as 120_I_RC or 60_RU_L.

Structurally equivalent material quantities of wood, steel and concrete for building structure were calculated and defined as thumb rules for estimation of total material in the Echo building. Data values to input in disassembly/ deconstruction (module C) of the assessment were obtained from the literature study. Other important data values such as carbonation potential of hempcrete and concrete were also reported from the literature study.

The proposed assessment method used material information from third-party verified EPDs and published literature to fills the gaps in LCA. However, some of the limitations of this method were also acknowledged. These include the impractical approach to achieve 100% of an end-of-life scenario, assumption of 120 years life span of structural materials, and unaccounted consequences arising from alternate material use. With these limitations, the results were believed to ***provide theoretically precise comparison of carbon emissions between materials, but not the actual impact of building.***

06 | Analysis

6.1 Echo building data

The sectional drawing details along with the material quantities of Echo building were studied to assess the total material quantities required in the project. Table 9 shows the identified materials in the building along with other possible material solutions. The alternate choices of material were limited to some conventional options such that sufficient literature and EPD data could be obtained.

The building materials identified for the analysis were also limited to the structural elements, as the other interior building elements greatly varies from architect to architect. Moreover, the structural elements are known to contribute the highest towards embodied carbon emissions and at the same time, they can be designed to have a service life of over 100 years.

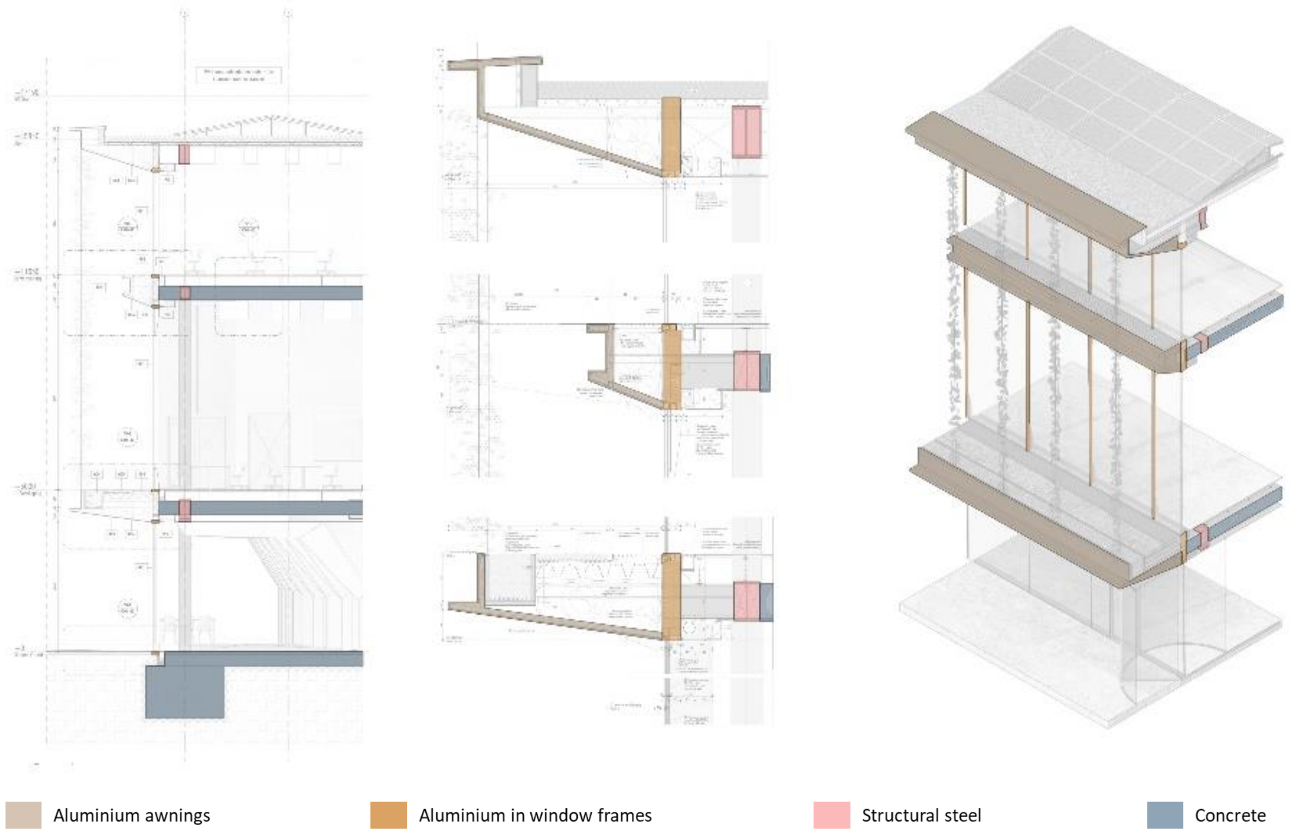


Figure 29: Materials identified in Echo building sectional details (Source: Author)

Table 9 also shows the difference in material quantities required for the building to have similar structural performance. The final results would therefore show the impact of the whole building rather than per square meter building area. In further sections, a comparison between different building elements are also shown to compare their relative impacts in the total embodied carbon emissions of the building.

Insulation materials in the acoustic felt wall panels and ceiling panels were also identified to be assessed and compared with other suitable materials. Table 9 shows the proposed quantity of insulation in one column and combined insulation quantity in the other columns. Section 6.2.4 further explains the process of material selection.

<table>
<tr><th>Building element analysed</th><th>Length/ Area</th><th>Existing Design Material</th><th colspan="5">Proposed Materials</th></tr>
<tr><td rowspan="2">Columns</td><td rowspan="2">371 m</td><td>Steel</td><td colspan="2">Wood</td><td colspan="3">Concrete (3 types)</td></tr>
<tr><td>77,072 kg</td><td colspan="2">130,387 kg</td><td colspan="3">292,950 kg + steel</td></tr>
<tr><td rowspan="2">Beams</td><td rowspan="2">1350 m</td><td>Steel</td><td colspan="2">Wood</td><td colspan="3">Concrete (3 types)</td></tr>
<tr><td>436,440 kg</td><td colspan="2">139,852 kg</td><td colspan="3">2,618,070 kg + steel</td></tr>
<tr><td rowspan="2">Slabs</td><td rowspan="2">4055 m^2</td><td>Hollow concrete slab</td><td colspan="2">Wood</td><td colspan="3">Concrete (2 types)</td></tr>
<tr><td>400mm thick</td><td colspan="2">180mm thick</td><td colspan="3">400mm thick</td></tr>
<tr><td rowspan="2">Façade (double glazing)</td><td rowspan="2">2758 m^2</td><td>Aluminium frame</td><td colspan="2">Alu-wood frame</td><td colspan="3">PVC-U frame</td></tr>
<tr><td>13,321 kg</td><td colspan="2">5,455 kg aluminium + 9,092 kg wood</td><td colspan="3">23,495 kg PVC U + 15,830 kg steel</td></tr>
<tr><td rowspan="2">Façade Awning</td><td rowspan="2">2170 m^2</td><td>Aluminium</td><td colspan="2">Wood</td><td colspan="3">Bamboo</td></tr>
<tr><td>15,320 kg</td><td colspan="2">16,900 kg</td><td colspan="3">26,908 kg</td></tr>
<tr><td rowspan="2">Wall finish and ceiling finish panel (insulation)</td><td rowspan="2">51.4 m^3</td><td>Rock wool</td><td>Glass wool</td><td>Hempcrete</td><td>EPS foam</td><td>Wood fibre</td><td>Cellulose</td></tr>
<tr><td>2,158 kg</td><td>5,654 kg</td><td>12,071kg</td><td>1,028 kg</td><td>3,233 kg</td><td>2,657 kg</td></tr>
</table>

Table 9: Existing and proposed materials for the Echo building (Source: Author)

6.2 Life cycle stages of materials

The analysis of materials in section 6.3 is based on the data collected from the third-party EPDs, One Click LCA generic data and relevant literature. The EPDs generally follow standard EN 15804 and 16485 (in case of wood). Data collected and assumed in this research is also made to follow the same standards as much as possible. As mentioned in EN 15804, scenarios relevant to each building must be individually investigated and reported to calculate the total impact of material over the lifetime of the building. Since the scenarios created in this research generally do not follow the scope of other EPDs, following data has been used for the building elements studied in the paper.

6.2.1 Columns, Beams and Slabs

The materials used in these structural elements are usually limited to the material families of concrete, wood, and steel (Appendix 12.3). However, different types of wood or concrete exist that are suitable for different applications. Therefore, the primary production emissions of these materials are based on their specific type while the end-of-life emissions are assumed to be similar for each scenario.

The life expectancy of columns, beams and slabs assessed in this report is taken to be the same as the assessment period, i.e. 120 years, based on the literature (Black Hills Professional Home Inspections LLC, 2016; Wacław, 2014). The materials may still be functional and have the possibility to be recycled, but they are assumed to not be fit for reuse after 120 years.

a. Concrete

There is a wide range of concrete materials available in the market. For this research, 3 types of ready-mix concretes are studied- standard concrete, concrete with 20% SCM and a concrete variant with 100% replacement of coarse aggregate (from Van Nieuwpoort Groep). The approximate embodied carbon emissions (module A1-A3) for these materials are 310, 180 and 84 kg CO_2/ m^3 respectively (Næringslivets Stiftelse for Miljødeklarasjoner, 2018; Van Nieuwpoort Groep, n.d.). All the results are inclusive of the carbon emissions from steel reinforcement.

The carbonation of concrete columns and beams are also taken into account as per the percentages explained earlier in Table 8. With the decreased quantity of OPC cement used in concrete type 2 and 3, the carbonation values are reduced. The values of carbonation in concrete is also verified with data from some EPDs (BRE, 2016; Souto-Martinez et al., 2018). For the precast hollow concrete slabs, the carbonation values are not considered for two reasons. Firstly, the slabs are covered with an additional layer of materials preventing the carbonation due to open atmosphere. Secondly, there are only limited research focussing on the carbonation of hollow concrete slabs.

End-of-life emissions for the recycling and reusing scenarios are calculated using the values from Table 7 along with the transportation emissions, which are assumed equal to A4 module. The recycling benefits of concrete as crushed aggregates are assumed to come from the avoided carbon emissions of aggregates used in concrete production (Bionova Ltd, n.d.). The reuse scenario may not be suitable for the ready-mix concrete columns but through further study of precast concrete columns, they can be assumed to have similar carbon footprint.

b. Wood

Glue laminated timber for columns, planed timber for beams and CLT for slabs were selected as material choices for analysis (Institut Bauen und Umwelt e.V. (IBU), 2013; The Norwegian Wood EPD Foundation, 2015; Vahanen Environment Oy, 2017). In all the cases, biogenic carbon was included in the calculations. However, the net impact of biogenic carbon is taken as 0 due to added carbon emissions in module C.

The scenarios for module C and D considered in all type of timber elements are landfill, incineration (with energy recovery), recycling to wood chips and reusing. The landfill scenario is assumed to produce gas that is combusted for energy recovery. Values are averaged out from multiples sources (Bionova Ltd, n.d.; thinkstep Pty Ltd & Stephen Mitchell Associates, 2017; Wood for Good, 2013).

c. Steel

Steel sections are common material choices for construction. The existing design scheme of Echo building also uses structural steel sections largely. Generic data of 90% recycled steel from One Click LCA is used for calculations, along with the deconstruction/ demolition values from Table 7 for module C-D scenarios.

6.2.2 Façade

The three conventional façade types- aluminium, wood-aluminium and PVC-U frames are assessed in this report (Appendix 12.3.4). It must be noted that timber frame façade is also possible but are not commonly available in market. This makes it difficult to find literature and EPD data on them, and therefore are not assessed as on option in this report.

Double glazing façade with equivalent properties were chosen in all the cases to have comparable results. The carbon emissions resulting from glass and other materials such as gaskets and screws are also included in the life cycle assessment. However, module C and D scenarios for all the materials consider a typical end-of-life for glass and other small components to highlight the difference between frame types. This is extracted from the existing market condition that recycles 60% of the glass and almost 90% of metal components. Rest of the materials are either sent to landfill or incinerated (Institut Bauen und Umwelt e.V. (IBU), 2017b). Module C and D calculates the total impact of all the replaced and initially installed windows.

The life expectancy of aluminium and wood-aluminium frames are assumed to be 60 years, while that of PVC-U frames as 40 years (European Aluminium, 2016; Institut Bauen und Umwelt e.V. (IBU), 2017b; Menzies, 2013; The Norwegian EPD Foundation, 2013). Therefore, the scenarios of reusing material after 60 years is not considered in their analysis. Only scenarios 120_I, 120_RC and 120_L would be relevant for this.

a. Aluminium frames

The aluminium frame windows are commonly used in building industry due to high recycling potential of material. The analysis is conducted for a double glazed non-operable aluminium frame window (European Aluminium, 2016). Since the aluminium frames are never sent completely for landfill or incineration, those end-of-life scenarios (120_I and 120_RC) are not considered in the report. The benefits in module D are net impacts of recycling after due subtraction of recycled materials in production stage.

b. Wood-aluminium frames

The biogenic carbon is included in the analysis both in module A and C with zero net impacts (The Norwegian Wood EPD Foundation, 2015). The end-of-life scenarios consider a standard recycling percentage for aluminium similar to module A. However, the share of wood is analysed in 3 scenarios of incineration, recycling, and landfill. Assumptions for values of module D are considered to be the same as the wood used in columns, beams, and slabs.

c. PVC-U frames

Unplasticized Polyvinyl Chloride (PVC-U) windows also consists of steel reinforcements. While the analysis considers a 100% recycling potential of PVC-U at its end-of-life, it must be noted that the primary production of windows cannot use more than 40% of recycled PVC-U. It is due to its degraded performance upon more recycling (Institut Bauen und Umwelt e.V. (IBU), 2017b). The end-of-life scenarios consider a standard option for the glass and steel as mentioned earlier. The benefits in module D are reported from the avoided emissions of recycled material and the thermal/ electrical energy produced in the different scenarios.

6.2.3 Façade awnings

The existing design proposes aluminium awnings on the exterior. Two alternative materials that show carbon sequestration potential (i.e. wood and bamboo) are studied for comparison. This may be subjective to every design as they are also guided by the architect's overall design concept.

The wood and bamboo awnings are assumed to have a life span of 40 years, thus, are replaced twice in the life span of 120 years of a building. The aluminium awnings are assumed to last as long as the building. Therefore, scenarios 120_I/RC/L were relevant for assessment of wood and bamboo awnings, while scenarios 120_RC, 60_RU_RC and 60_RC_RC were relevant for aluminium awnings (Appendix 12.3.5).

a. Aluminium

The aluminium composite panels from ALUCOBOND as proposed in the Echo building's design is assessed using the data from EPD (Institut Bauen und Umwelt e.V. (IBU), 2014). Since the aluminium panels are majorly recycled at their end-of-life, only the 100% recycling scenarios are considered for the analysis. This also allows for the panels to be reused at their end-of-life with regular maintenance during their service life.

b. Wood

Wood composite panels are assessed as potential alternate material for the façade awnings (Institut Bauen und Umwelt e.V. (IBU), 2015). The biogenic carbon is included in the analysis with zero net impact over its life. Assumptions for values of module D are considered to be the same as the wood used in columns, beams and slabs.

c. Bamboo

One of the only bamboo manufacturers, MOSO have published three EPDs for their products. MOSO Bamboo X-treme is chosen as a suitable material alternative for the façade awnings (CAPEM, 2017). The data for module C and D in incineration scenario was taken from the EPD. However, the landfill and recycling scenarios are assumed to function similar as wood, due to lack of information. Much like wood, bamboo also sequesters carbon during its production which is shown as biogenic carbon stored in module A and released in module C.

6.2.4 Insulation material

The interior wall finishes in the Echo building design proposes PET felt panels. These panels consist 50mm of rockwool layer as insulation. Additionally, 30mm of insulation is also identified for the ceiling insulation. The total volume of insulation used, i.e. 51.4 m^3 was set as the baseline option. To have a fair comparison between materials, the amount of material needed (in kg) for 1 m^2 panel area with a thermal resistance value of 1 m^2K/W was identified. It is also recognized as the functional unit for fair comparison between insulation materials (Schiavoni, D'Alessandro, Bianchi, & Asdrubali, 2016). A research study conducted by Schiavoni, D'Alessandro, Bianchi, & Asdrubali (2016) compares different insulation materials based on various data sources. It has reported the functional unit weight (in kg) of insulation material needed for 1 m^2 panel area with a thermal resistance value of 1 m^2K/W (Figure 30).

Material	f.u. weight (kg)	Thermal conductivity (W/m K)[a]	Energy consumption (MJ_{eq} per f.u.)	Global warming potential (kg CO_{2eq} per f.u.)	Approach and system boundary
Cellulose	2.34	0.039	19.39	0.73	CTGA, European
Cellulose	2.00	0.040	20.97	3.66	N.A.
Cork	5.00	0.050	257.98	5.72	CTGA, European
Cork	7.35	0.049	378.65	5.93	N.A.
Expanded clay (loose)	31.50	0.090	161.14	10.31	CTGA, European
Expanded perlite (panels)	4.50	0.050	67.31	3.99	CTGA, European
Expanded polystyrene	0.80	0.040	127.31	5.05	CTGA, European
Expanded polystyrene	1.13	0.038	118.67	8.25	N.A.
Expanded polyurethane	0.90	0.030	126.40	5.31	CTGA, European
Expanded vermiculite (loose)	6.30	0.070	53.37	3.36	CTGA, European
Extruded expanded polystyrene	1.75	0.035	127.31	13.22	CTGA, European
Glass fibers	0.80	0.040	134.17	7.70	CTGA, European
Glass wool	8.00	0.050	229.02	9.89	CTGA, European
Hemp	1.20–1.90	0.038–0.040	23.65–35.55	0.17–0.26	CTGR, N.A.
Jute fibers	5.00	0.050	105.54	2.79	CTGA, European
Kenaf	1.52	0.038	59.37	3.17	CTGA, Italy (400 km)
Kenaf fibers	1.90	0.038	42.32	1.13	CTGA, European
Natural pumice (loose)	55.00	0.110	1.82	0.08	CTGA, European
Polyurethane	0.96	0.032	99.63	6.51	N.A.
Recycled PET	1.07	0.036	83.72	1.78	CTGA, Italy
Recycled PET (commercial)	1.48	0.037	21.06[a]	3.12	CTGR, N.A.
Recycled textile (commercial)	1.79	0.036	17.57[a]	1.55	CTGR, N.A.
Sheep wool	0.76	0.038	17.12	1.46	CTGR, N.A.
Stone wool (commercial)	1.18	0.037	20.75	1.45	CTGR, Western European market
Stone wool	1.20	0.040	53.09	2.77	CTGA, European
Stone wool	2.40	0.040	63.34	3.62	N.A.
Wood wool	12.60	0.070	255.36	1.56	N.A.

N.A. not available.

[a] Information reported in this paper have been reprocessed through SimaPro software to consider the current scenario.

[b] Original data referred to 1 kg of product and use phase not considered.

Figure 30: Comparison table including f.u. weight (in kg) of insulation materials with similar thermal resistance (Schiavoni et al., 2016).

Figure 30 shows a comprehensive list of both conventional materials used for insulation. This list of insulation materials gets even longer if we include unconventional materials such as cotton, date palm, pineapple leaves, etc. To limit the scope of analysis for this research, only some materials with available EPD data and commercial applications were selected.

The life expectancy of insulation materials is commonly taken the same as that of the building. The same is assumed for the analysis. The EPD data for all the materials has also been used to verify the module A values (Bau EPD GmbH, 2014; BRE Global, 2015; EVEA, 2018; Institut Bauen und Umwelt e.V. (IBU), 2017a, 2020). Life cycle assessment of hempcrete is well investigated in these researches along with the carbonation potential during its life (Andersson & Björhagen, 2018).

The module D benefits for all the materials are not considered in the assessment, unless they are related to thermal/ electrical energy recovery from the incineration of materials themselves. This is due to the following reasons:

a. the benefits are commonly not available in the EPDs
b. they also take packaging materials into account, when incinerating for energy recovery
c. the share of module D values are significantly lower in the total assessment
d. most of the insulation materials are always reused/recycled, and thus, reflect these benefits in module A calculations

6.2.5 Summary

The Echo building was divided in its building components such as columns, beams, slabs, façade, awnings, and insulation materials to assess their impacts. The proposed materials for each building component were ***reported with their total quantities for the assessment.***

The assessment method proposed earlier was applied to analyse each material option for all the possible end-of-life scenarios. Although the structural components could easily be assessed with one life span of materials for 120 years in building, other components such as façade were assessed using material replacements. Inapplicable end-of-life scenarios such as incineration or landfill of steel were not reported as they would never be a 100% scenario.

The data values for each module were verified with multiple sources to avoid errors. Moreover, the analysis was an iterative process with careful interpretation to reach the final results.

6.3 Analysis and interpretation of results for each building element

Appendix 12.3 shows the graphs generated for the building elements and their material options as discussed in Table 9. Each graph presents different scenarios for a particular material choice for a building element. It shows the carbon emissions released into the environment above the X-axis and carbon emissions saved/reduced from the environment below the X-axis. The assorted colours within a bar graph indicates the carbon emissions at each life stage (module) of the material. The net impacts are marked using red dashed line to compare results between different scenarios.

6.3.1 Columns, Beams and Slabs

Appendix 12.3 presents the material options for columns, beams, and slabs in the Echo building. Using information from the graphs in the appendix, Figure 31, 32 and 33 summarizes the results at a uniform scale with all materials and their scenarios.

Figure 31: Material options and their different scenarios for columns presented at a uniform scale (Source: Author)

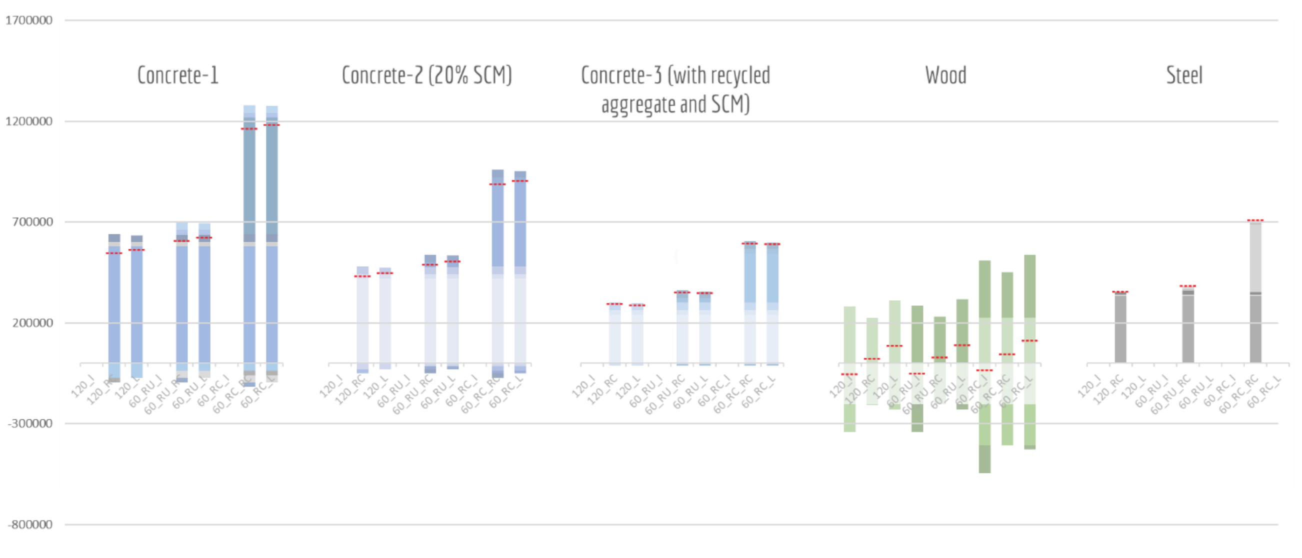


Figure 32: Material options and their different scenarios for beams presented at a uniform scale (Source: Author)

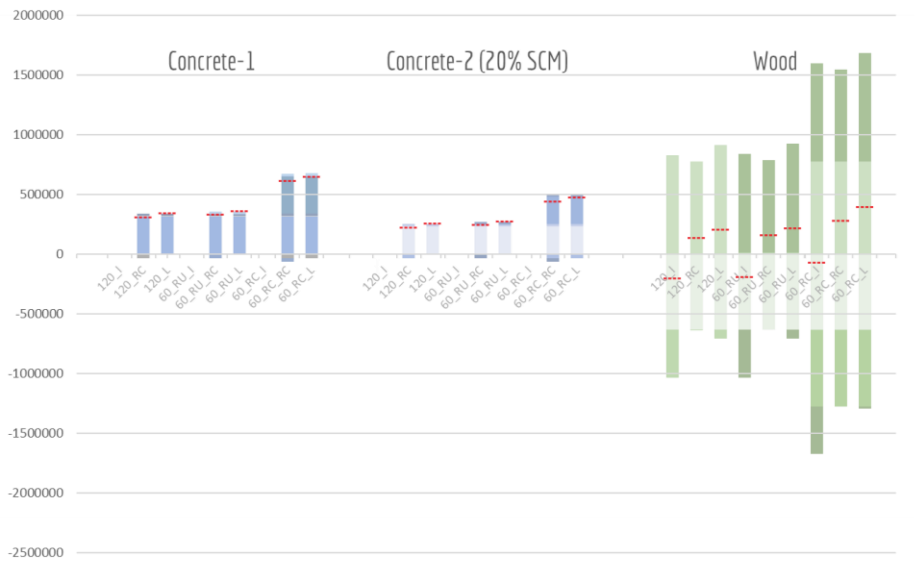


Figure 33: Material options and their different scenarios for slabs presented at a uniform scale (Source: Author)

All the scenarios of wood show high peaks on both positive and negative sides of carbon emissions. It is due to the enormous amounts of biogenic carbon flowing through the environment into the trees, getting stored in timber structure and then finally getting released back into the atmosphere upon incineration. The higher peaks in scenarios of 60_RC represents twice the amount of carbon flows due to the 2 life cycles of building. The carbon benefits of concrete shown below the x-axis represent their carbonation phenomenon occurring over its lifetime and the benefits due to recycling of concrete waste as aggregates. It can be seen that the benefits of other material options are not nearly as much as that from wood.

The net impact of three scenarios (i.e. 120_I, 60_RU_I and 60_RC_I) of using timber as structural elements show high potential in reducing the carbon emissions of the building. With the mentioned assumptions, these scenarios even show potential to be carbon negative. Although the landfill scenario of wood shows some potential, it should be considered the least preferred choice. Landfilling wood waste doesn't only fail to do energy recovery, but it also may be hazardous due to its treatment in production phase.

Steel with 90% recycled material is used in the analysis which is the reason the total impact from steel is within the range of other materials. While conducting the analysis using steel with lower recycle fraction, three times higher carbon emissions were also observed. This indicates the importance of using recycled steel with the highest recycled content possible. The carbon benefits are not given to steel as the benefit of recycling is already added in the production phase.

Interpretation

The carbon emissions of concrete and steel go even higher than the positive peaks of wood in case of beams. This can be justified by the ratio of material quantities needed for beams (as shown in Table 6). The volume of concrete used for beams is more than 3 times the volume of wood. Additionally, the production phase of wood requires the least amount of energy in all building elements, giving it an edge over steel and concrete. The incineration of wood also proves to be a crucial factor in reducing the carbon footprint of the construction.

The current design scenario of Echo building with a life of 60 years and steel column-beam structure would be among the highest carbon emitting scenarios. The combined emissions of steel columns and beams with 60_RC_RC scenario would sum up to 833.7 $MtCO_2$ eq. If this is to be compared with the best scenario seen from wood (120_I) columns and beams, it would roughly ***reduce the environmental impact by 115% (or 952 $MtCO_2$ eq.).*** As for the comparison between concrete hollow slabs in proposed design and the best scenario of wood slabs, ***reduction of 135% (or 818 $MtCO_2$ eq.) in carbon emissions is estimated.***

6.3.2 Façade

The three types of façade analysed in this report are aluminium frame, wood-aluminium frame and PVC-U frame façade. Appendix 12.3.4 presents the findings as bar graphs for different scenarios for the materials. As the life expectancy of façade is not more than 60 years, the scenarios for buildings with 120 years life and replacement of façade is considered. Figure 34 shows the comparison between different materials and their scenarios.

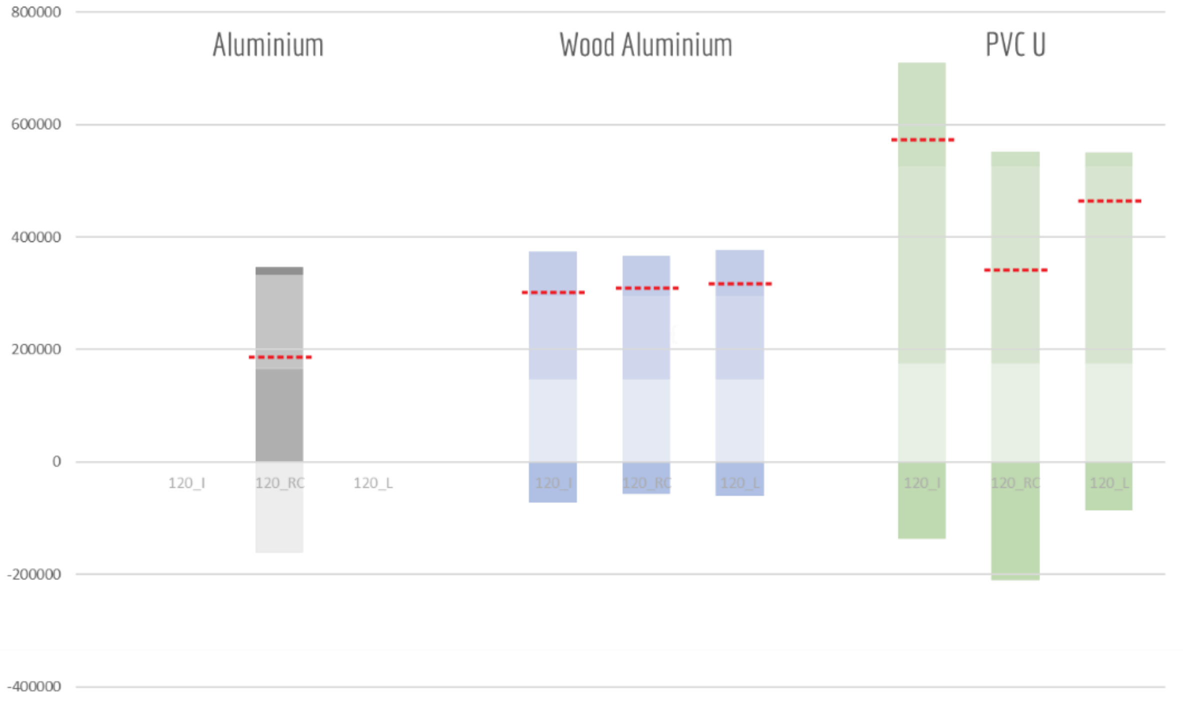


Figure 34: Material options and their different scenarios for façade presented at a uniform scale (Source: Author)

In this assessment, the aluminium frames are seen to have negative carbon emissions. This is due to the recycling process and benefits arising from them. Unlike structural steel shown in previous section, only part benefits of recycling is added in the primary production phase of aluminium. The net benefits of recycling more aluminium than used is counted towards the module D benefits. Wood-aluminium window frames show slightly higher carbon emissions than aluminium frames. The negative emissions are partly a result of energy recovery from wood incineration and partly from aluminium recycling. The actual wood content is only 20% of the total mass resulting in lesser potential of energy recovery.

PVC U window frames have slightly higher production emissions, but due to shorter life expectancy, they are replaced twice in the building life cycle. This results in higher carbon footprint. It is also evident from Figure 34 that PVC U frames have higher energy recovery potential from incineration. Although the landfilling of PVC U frames show lower emissions than incineration, they must be avoided as it takes decades to dispose.

Interpretation

The aluminium frame windows are seen to have the lowest net carbon emissions due to higher recycling benefits at the EOL. They are better than the wood aluminium frames as the actual wood content is only 20% of the total mass resulting in less potential for energy recovery. Moreover, the energy spent on deconstruction of wood-aluminium frames would have a higher impact on carbon emissions as the disposal of each material type would have to be carefully done.

The total carbon emissions from 120_RC scenario of ***aluminium frame windows are calculated to be 186 $MtCO_2$ eq.*** which is the best suited scenario for Echo building's façade.

6.3.3 Façade awning

The existing building design consists of aluminium façade awnings as cladding elements. These were assessed against 2 material options- wood and bamboo. Appendix 12.3.5 presents the findings as bar graphs for these material options and Figure 35 shows the comparison between their scenarios and net impacts.

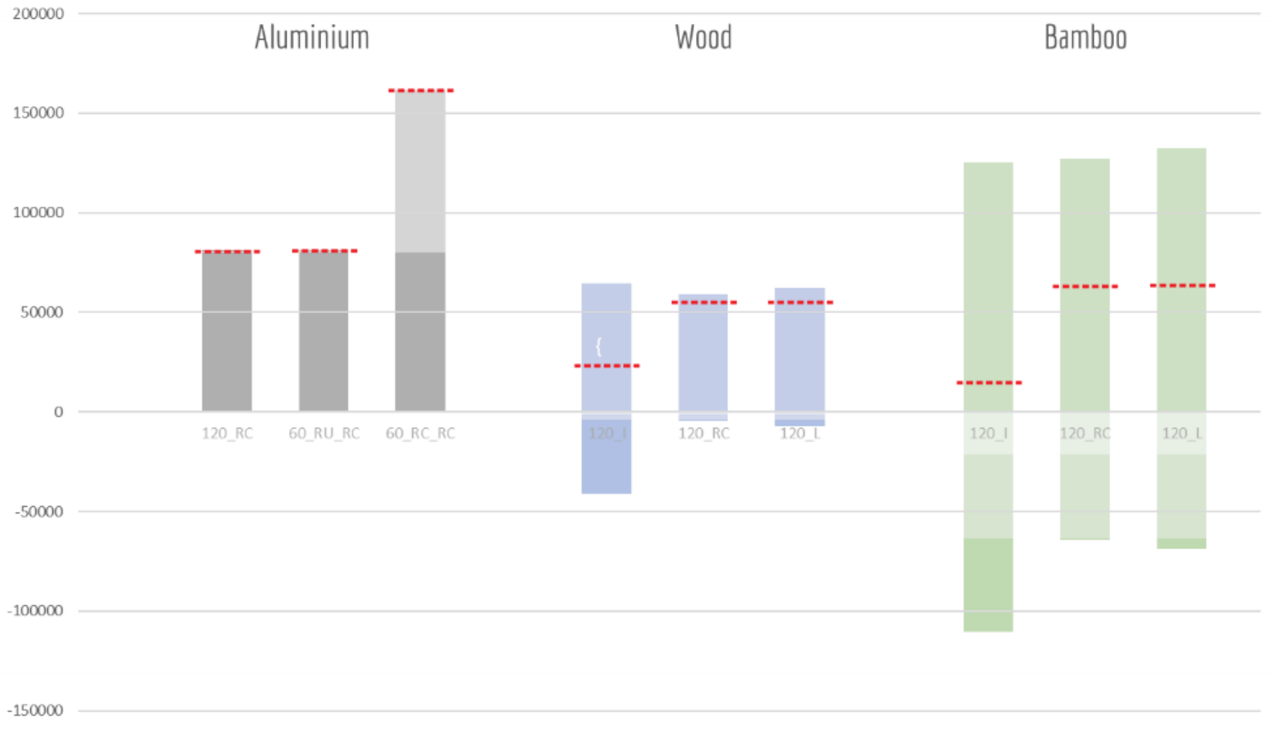


Figure 35: Material options and their different scenarios for façade awnings presented at a uniform scale (Source: Author)

As the aluminium panels have the potential to be used for longer life, a scenario for 120 years life span is shown for aluminium without any replacement. However, bamboo and wood panels are assumed to be replaced twice in the building's life cycle of 120 years, and collective emissions from all the material used are shown in the bar charts of scenarios.

Interpretation

The wood and bamboo panels have much lower primary production carbon emissions than aluminium. While both benefit from energy recovery upon incineration at EOL, bamboo has slightly higher energy recovery potential, that lower its total environmental impact.

The higher peaks of bamboo on either side of the x-axis can be explained by the higher carbon sequestration potential of bamboo during its growth phase. Thus, the biogenic carbon flows from sequestration and incineration are higher in bamboo but their net impact in environment is still assumed to be zero.

Bamboo panels are seen to be the suitable alternative for façade awnings as compared to the proposed aluminium composite panels. The calculations show a ***reduction of 90% carbon emissions (or 146 MtCO$_2$ eq.).*** For applications where the use of bamboo products is feasible such as lightweight framing or cladding, they must be preferred to reduce the burden on use of wood. Therefore, a balanced use of bamboo and wood in a building must be practiced.

6.3.4 Insulation material

While many material options exist for insulation, a comparison of 6 conventional materials was drawn. Appendix 12.3.6 shows all the bar graphs for the assessed materials and Figure 36 shows the comparison between them.

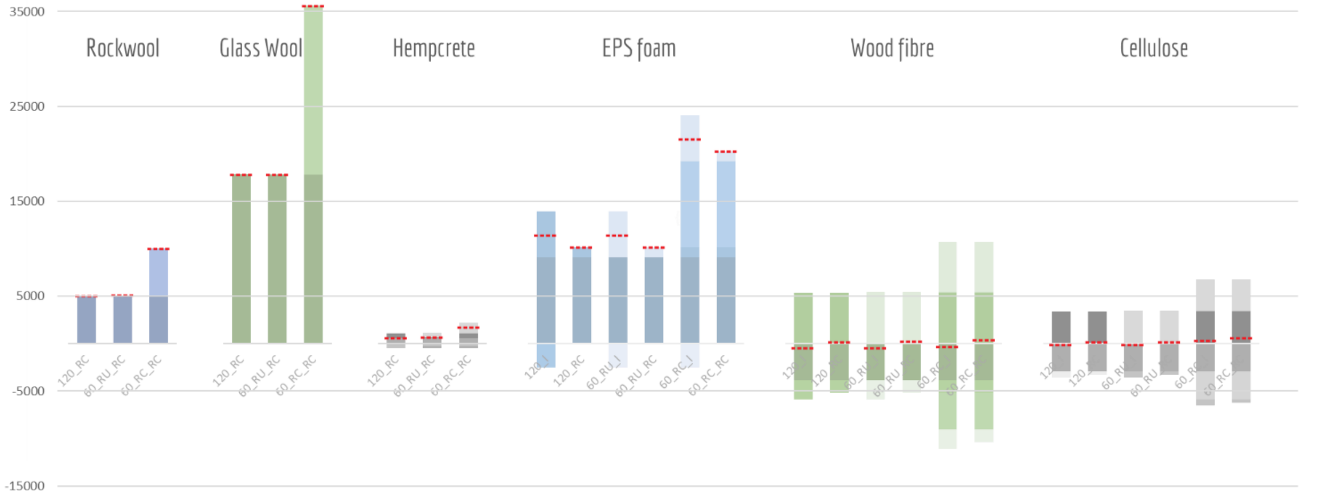


Figure 36: Material options and their different scenarios for insulation materials presented at a uniform scale (Source: Author)

All the natural materials are seen to have much lower environmental impact than the conventional materials. Some insulation materials such as EPS or Mineral wool have around 100 times higher environmental impact as compared to materials like wood fibre. Besides having lower production energy demand, wood fibre and cellulose insulation have higher energy recovery potential upon incineration, which makes them a better choice. Almost all the scenarios for wood fibre, cellulose and hempcrete are suitable for the application.

Interpretation

The insulation materials such as rockwool and glass wool have higher carbon footprint due to the higher energy required in the extraction process of raw materials. It is also understood from the literature that the production process of these materials consumes more fossil fuel energy. On the other hand, materials such as hemp, wood fibre and cellulose are produced from locally available material that also do not require high production or processing energy. Thus, the overall emissions of such nature-based insulation materials are seen to be lower than the other materials.

The reduction in carbon emissions from proposed insulation material, i.e. rock wool, to the best scenario of wood fibre (120_I) would be around ***105% (10.5 MtCO_2 eq.***). The use of energy-intensive and non-renewable material sources must be avoided as there are more and more local insulation materials available in the market. One of the limitations of using these local insulation materials is their susceptibility to water damage in case of incorrect installation.

6.3.5 Summary

The proposed materials for each building component was analysed and reported using bar graphs. The bar graphs representing carbon emissions over the life span of 120 years in different scenarios were produced. Each bar graph consisted of assorted colour shades representing the 4 modules of LCA (A-D). The combined impact of bar graph was represented by a red dashed line to draw comparison between the material scenario.

The lowest carbon footprint realised in structural elements was with the use of wood, in façade awnings using bamboo, and in insulation material using wood fibre. More specifically, the scenarios with incineration at their end of life showed the lowest carbon emissions due to potential of energy recovery. Aluminium frame façade as existing material choice was seen to have the lowest carbon footprint due to their high recycling potential. It would be fair to conclude that the bio-based material choices had much lower life cycle carbon emissions than other alternatives. The reason behind this is their ***potential use as biomass for energy.*** However, it is important to note that the carbon emissions of type-3 ***concrete reaches close to that of wood*** when the energy recovery potential is unaccounted.

Results of other building components are ***largely influenced by the choice of life span*** assumed for the buildings. This is due to longer life span of materials such as aluminium frame façade or aluminium awnings as compared to PVC frame façade or bamboo awnings. However, they ***must not be looked separately*** from the building and therefore, to maintain consistency in results, the suitable material options were proposed from this analysis.

6.4 Conclusions

6.4.1 Identifying the best/worst case scenarios

The individual analysis of building components allowed us to understand the carbon emissions from each life stage of the material options. The interpretation of results was an iterative process with the calculation stage, as the difference in scope of analysis between two materials had a drastic impact on the output.

Using wood structural elements showed better results in comparison with recycled/ reused concrete and steel structure. This is due to the high carbon emissions from the end-of-life processes in concrete and steel. The incineration of wood and energy recovered balances the carbon emissions resulting from additional material use. However, from the perspective of depletion of materials, it must not be practiced.

Defining life span and structural materials

- **Based on the analysis, designing an all wood structure (columns, beams and slabs) with 120 years life span and a 100% incineration EOL scenario would result in the lowest carbon emissions.** Due to the potential of energy recovery from wood incineration, a net impact of (minus)-327 MtCO_2 eq. is calculated.
- **Based on pre-determined short-life (60 years) scenario, designing an all wood structure with circular strategies would result in the lowest carbon emissions for a 60-year building scenario.** The building elements designed with the possibility of disassembly and reuse at their EOL, installed in another building for 60 years and ultimately incinerated show an overall impact of (minus) -307.5 MtCO_2 eq.

The structural elements designed in other permutations upon use of different materials are also analysed to give a perspective of all possibilities. As the architects and engineers may have various reasons to use/ not-use some material options, a comprehensive summary of all construction possibilities is reported ahead. Figure 37 and Figure 38 summarizes the impact of using of different materials as columns, beams or slabs. While Figure 38 shows the building scenario with circular construction of 60 years, Figure 37 shows a durable building scenario of 120 years.

The icons next to each bar depicts the type of construction with material used in each structural element- column, beam and slab. To compare the best scenarios of each material, type-3 concrete with 20% SCM and recycled concrete aggregates is used with an EOL of recycling. Wood is assumed to be incinerated as that is seen to have the maximum potential in reducing carbon emissions.

Interpretation

The figures indicate reduced carbon emissions in structure as more wood is used in the construction. Moreover, the importance of certain building elements can also be understood. For instance, the use of wood slabs contributes the most towards reducing the overall carbon footprint as the combinations with wood slabs are seen to be on the top. Contrarily, use of concrete slabs seem to increase the carbon footprint.

Other than an all-wood construction, combination of wood slabs and beams with concrete or steel columns also show potential in achieving a carbon negative structure. One reason for this is ***less quantity of materials used in columns.*** Another reason would be the ***better structural performance of steel and concrete in compression than wood.*** This may also lead to oversized wood columns that occupy more space in the building. As the built-up area has high economic impact, the choice of materials in structural elements are also dictated by the space used by them in construction.

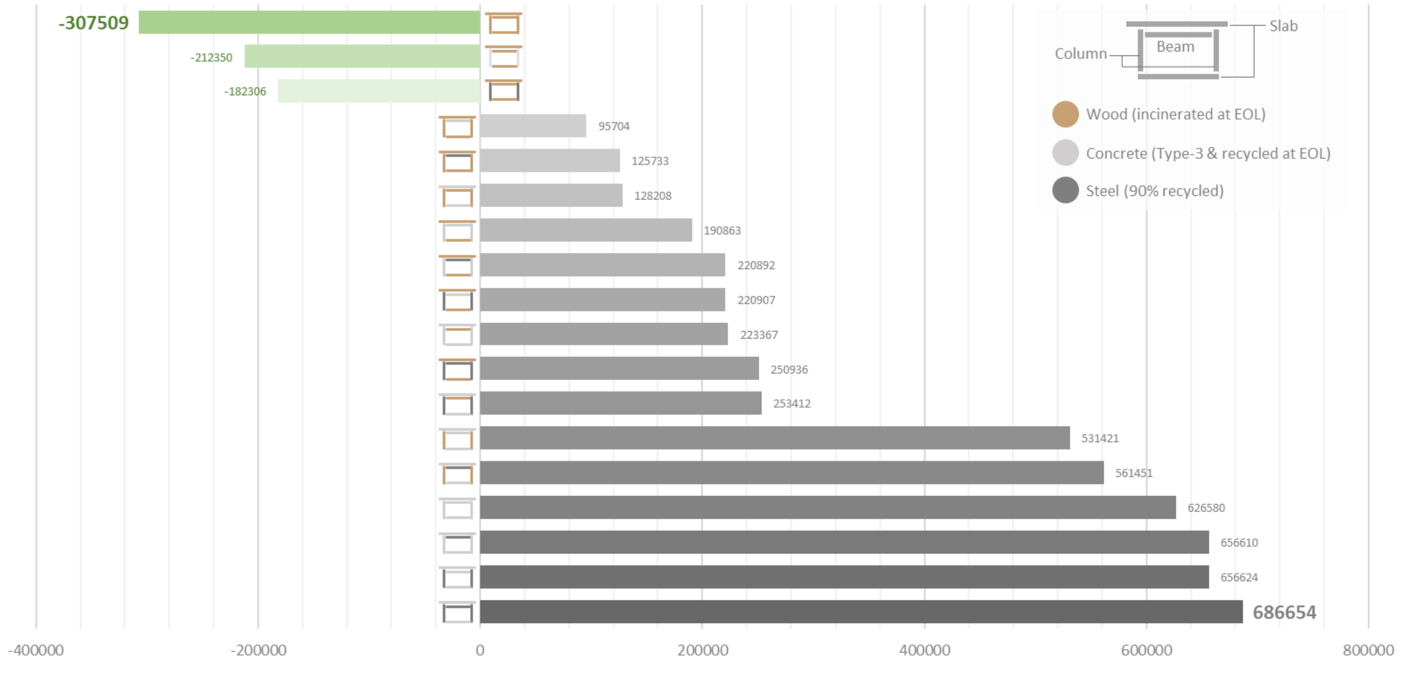


Figure 37: Best to worst case scenario of alternate material use in structure for a circular building with 60 years life span (Source: Author)

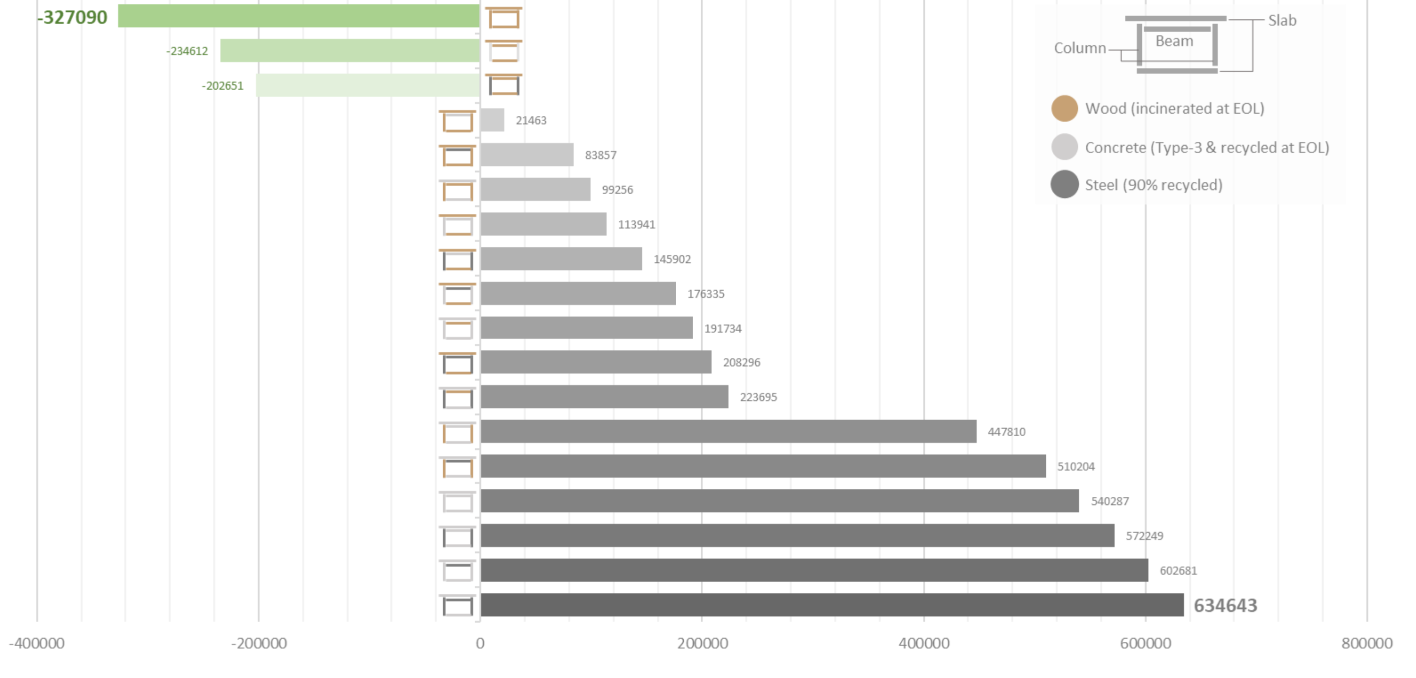


Figure 38: Best to worst case scenario of alternate material use in structure for a building with life span of 120 years (Source: Author)

Building element analysed	Existing Design Material and carbon footprint (*MtCO2 eq.)*	Proposed Materials and carbon footprint (*MtCO2 eq.)*	Percentage reduction in carbon emissions
Columns	Steel sections	Glue laminated timber	149%
	125.3	-61.8	
Beams	Steel sections	Planed timber beams	108%
	708.4	-56.8	
Slabs	Hollow concrete slab	CLT slab	135%
	609.6	-208.6	
Façade (double glazing)	Aluminium frame	Aluminium frame	-
	186.4	186.4	
Façade Awning	Aluminium	Bamboo	91%
	161.5	14.9	
Insulation Material	Rockwool	Wood fibre	105%
	10.0	-0.5	

Table 10: Existing and proposed material carbon emissions for each building component (Source: Author)

Table 10 summarizes the carbon emissions from existing and proposed material alternative. The combined impact of construction was compared by using the existing design materials and the proposed alternatives. As there was no better alternative for façade and the impact of insulation materials were too less compared to other building elements, only the structural elements and façade awning were here forth considered for discussion. The two most suitable alternatives found from the analysis for the existing design are as follows:

a. **Wood structure in a building with longer lifespan (120_I)** and **bamboo façade awnings** replaced after 40 years shows a potential in reducing the carbon emissions by **1917 MtCO2 eq. (or 119%)**

b. **Wood structure in a building with circular design strategies and shorter lifespan (60_RU_I)** and **bamboo façade awnings** replaced after 40 years shows a potential in reducing the carbon emissions by **1897 MtCO2 eq. (or 118%)**

The reuse of materials drastically reduces the overall impact (60_RU_I) and is almost comparable to scenarios with a 120-year life span construction (120_I). This is due to significantly low amount of carbon emissions in the process of circular use. These carbon emissions can be **assumed negligible in comparison with the embodied carbon emissions of the materials.** Due to this reason, we now also see a shift in architecture practice from traditional to circular design ideas.

6.4.2 Comparison between existing and proposed design of the Echo building

The analysis of each building element highlighted the impact of proposed material alternative. Figure 39 presents the combined impact of all the elements analysed in the report. The pie charts show the share of each building element in total carbon footprint of the construction.

In the blue pie chart, beams can be seen as the highest contributor, while the insulation materials have the lowest impact. The green pie chart shows the carbon emissions from proposed material alternatives. The pie slices of columns, beams and slabs are seen going inwards is due to the negative carbon emissions resulting from the use of wood structure. As the aluminium façade already has the least carbon emissions than its alternatives, the pie slice remains unchanged. The façade awnings do have the potential to reduce its impact by using bamboo panels, therefore, the orange pie slice is shown as the new impact from the use of bamboo. An impressive result can be seen from the pie slice of slabs. While all three- beams, columns and slabs result in negative carbon emissions upon the use of wood, the impact of using wood slabs is much more than the use of wood beams and columns.

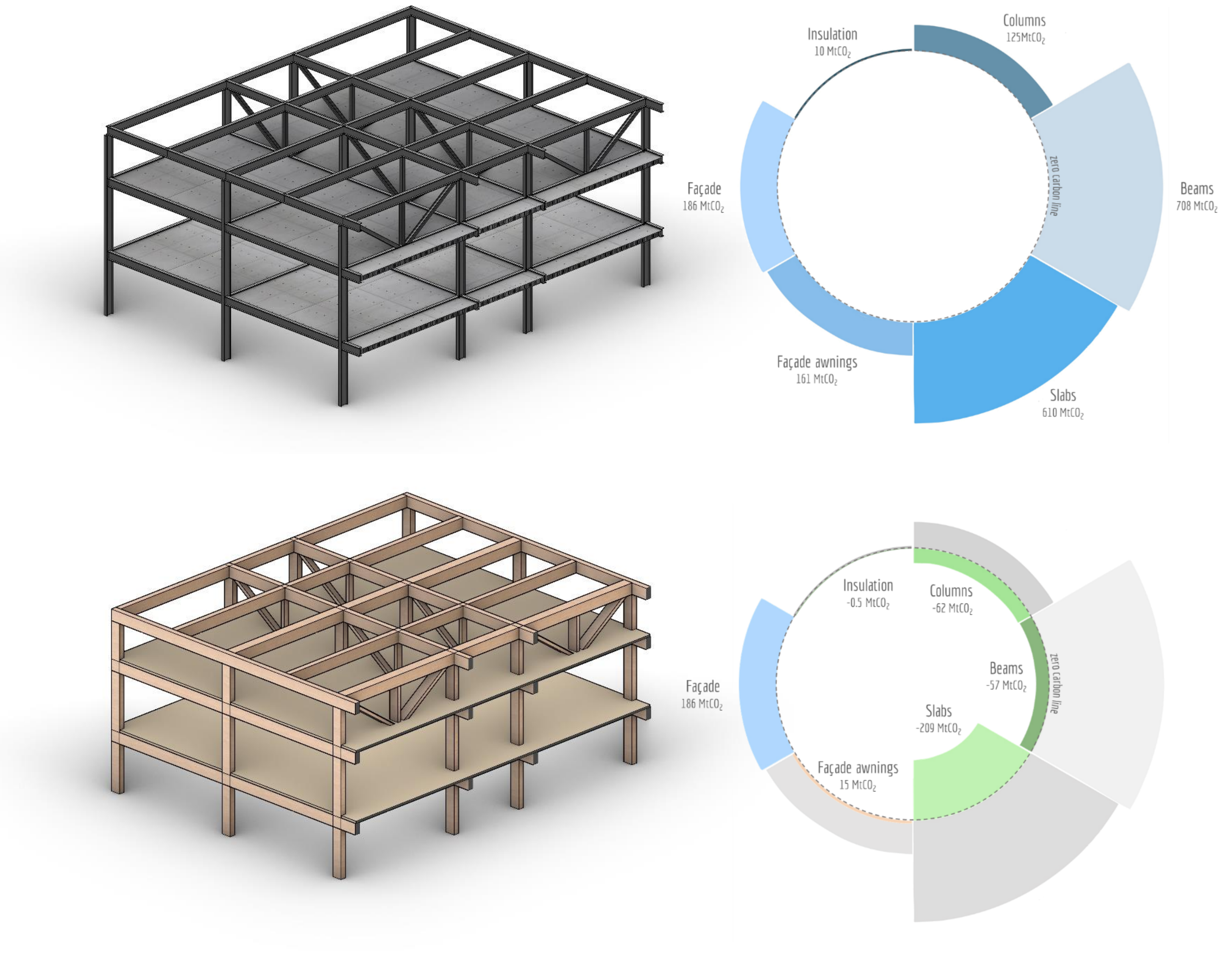


Figure 39: Comparison of total impact of building materials on the carbon emissions of the construction. The steel structure and pie chart on the top shows the existing design. The wood structure and pie chart on the bottom shows the proposed design. (Source: Author)

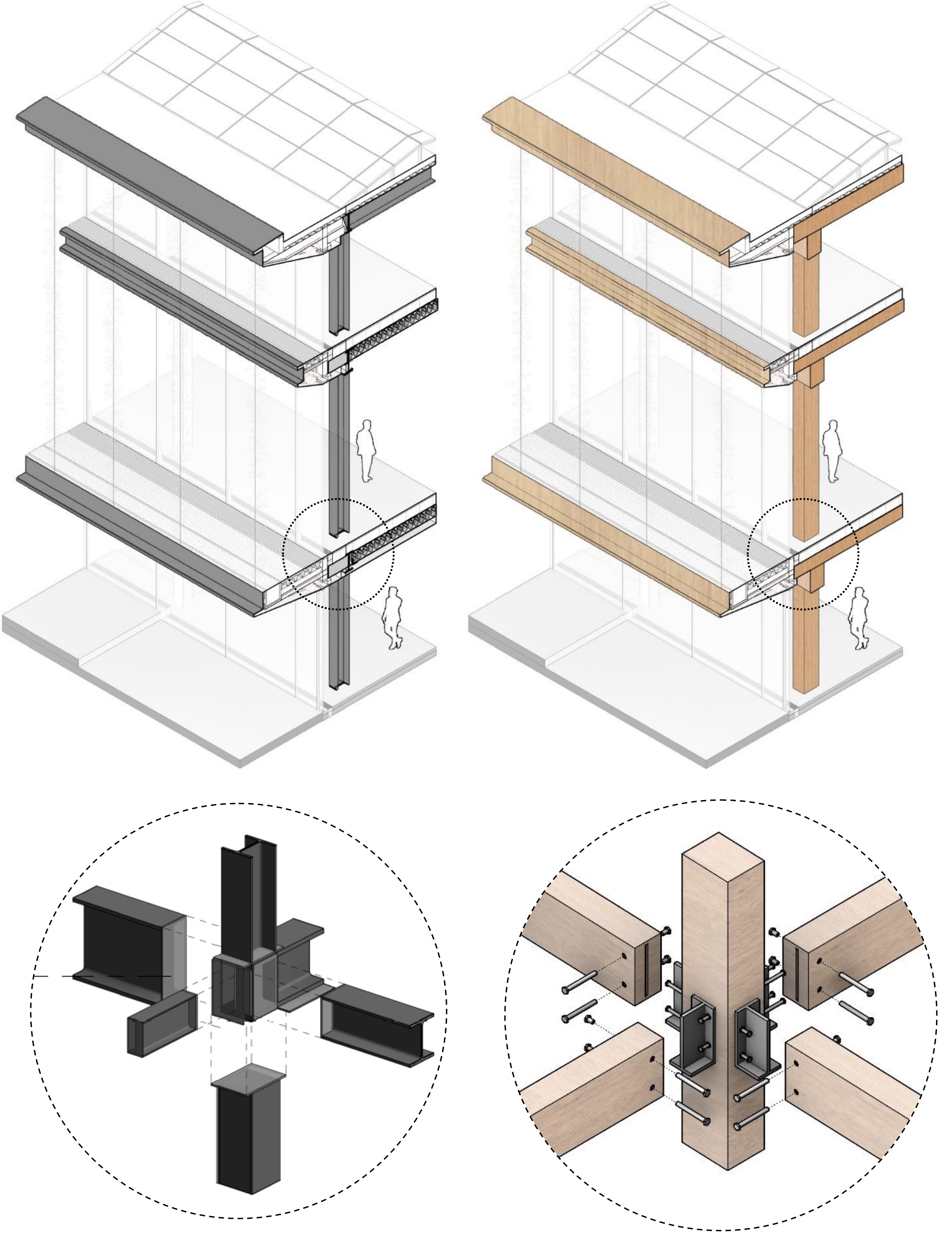


Figure 40: A comparison between technical detail in existing design and concept detail of proposed solution (Source: Author)

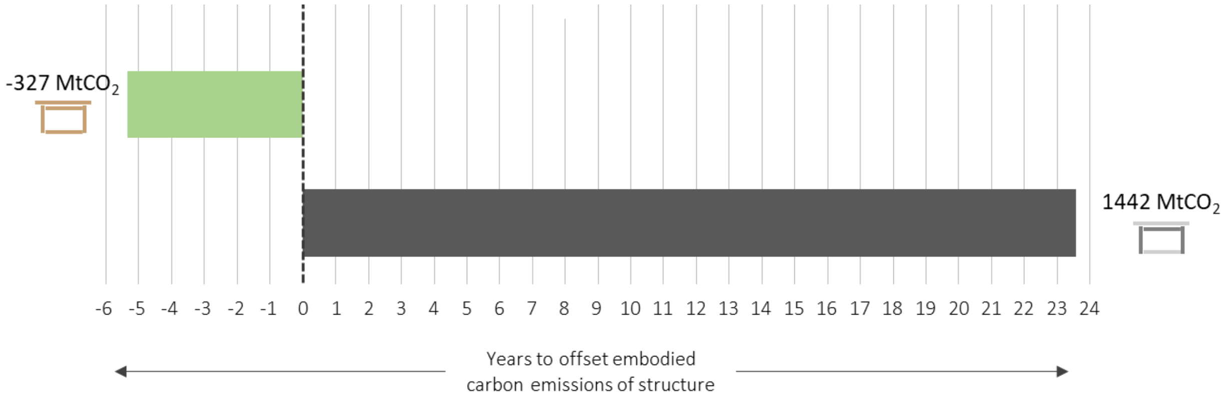


Figure 41: Carbon offset period in the proposed and existing design options (Source: Author)

The energy and carbon calculations of the Echo building shows an overall net positive energy performance. This implies that the renewable energy produced (onsite and offsite) is greater than the energy consumed in building operations. This renewable energy is calculated to offset 61 $MtCO_2$ eq. carbon emissions each year for the complete construction. The total carbon footprint of the building including the interior construction and services, must be divided by this value (i.e. 61 $MtCO_2$) to obtain the number of years before the building is considered **carbon neutral**.

Only considering structure of the building, it can be seen from Figure 41 that the carbon offset from renewable energy would take almost 24 years to balance the embodied carbon emissions. On the other hand, the proposed design itself has the potential to balance the carbon emissions from suggested building materials. As and when the building completely offset its embodied carbon footprint, it can be assumed that the design would have met **zero carbon goal in a few years already.**

The above interpretation of analysis highlights the importance of material selection in a building construction. The energy intensive production process of concrete and steel causes the total carbon emission of structural elements to be 122% more than that of wood frame construction. As discussed before, the low primary production emissions of wood and high energy recovery at its end-of-life proves to be beneficial in reducing the carbon emissions of structure. While Figure 41 shows the impact of high-carbon concrete in the existing design, the low-carbon concrete analysed in the report also fails to match the impact of timber construction. The number of years to offset the carbon emissions in this case would reduce to around 11 years.

The conceptual design phase allows more flexibility to compare the materials and different types of construction- circular or durable. As the design evolves in the development phase, it becomes more and more challenging to alter the material choices. It is, therefore, crucial to assess the impact of materials at an early-design stage. The existing design of Echo building uses suitable design strategies. Still, it has a potential to further bring down the carbon footprint of structure by 120% and reduce the carbon offset period of the construction by almost 30 years.

Strategies involved

The results are biased in terms of only reducing carbon emissions from the atmosphere, either using carbon sequestration during growth of trees or bamboo, or carbon offset potential from energy recovery at their EOL. They do not consider the economic impacts or material depletion rate from the surroundings. Therefore, the material solutions must not be looked in isolation to guide the design. Some strategies in relationship with the proposed materials must also be followed to achieve the expected results:

a. There are certain design prerequisites of reducing the carbon emissions using the two scenarios of long lifetime (120_I) and short lifetime but circular building (60_RU_I). Since the building use often change over the years, the buildings need to be designed robustly. Although the materials chosen in the Echo building have a higher impact on the total carbon emissions, the design strategies used may still be applied to the proposed option. Some of the strategies used in building design to allow robustness are:

For 120_I lifetime scenario

The building and building elements are both assumed to have a service life of 120 years. The buildings face some challenges such as changing needs of the society and need for mid-life renovation. To address such challenges, some design strategies that must be followed are:

- Designing building in independent layers (Figure 42), such as avoiding embedded ducts in structure or built-in wall storage units
- Overdesigned structures to accommodate future loads
- Providing slightly higher floor-to-floor heights to facilitate more functions
- Open floor plan to allow multipurpose use of spaces
- Use of mobile internal walls to allow flexible layouts
- Regular maintenance and replacement of building elements

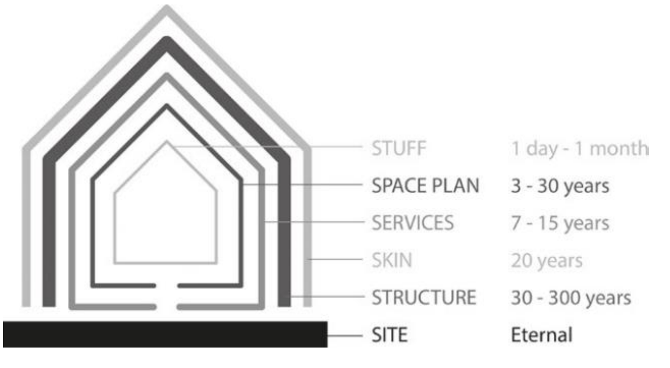


Figure 42: Building in layers to allow independent transformations (Brand, 1995)

For 60_RU_I lifetime scenario

The reuse of building components assumed in this scenario requires the building to be designed with principles of DfD (Design for Disassembly). The principles below must be followed to ensure that the building component is technically suitable and is not damaged during deconstruction:

- Simple and standard construction to allow workability
- Modular design not just within the building but also across different typologies of construction to allow reusability of component
- Minimize different type of connections, materials, and connectors to ease disassembly process and material identification
- Using dry connections to ease the disassembly process
- Lightweight construction to allow easy deconstruction and manual workability
- Keeping on-site replacements for possible building components

b. The end of life scenarios were prepared to give an understanding of difference between the impacts of various disposal options. While the incineration of wood and bamboo seems to benefit the carbon footprint of construction, they only provide part of the bigger picture. The maximum service life for the materials were assumed to be the same as that of the building/component. Thus, the resulting scenario suggests incineration after the use of material. However, the proposed EOL scenario, i.e. incineration, must be understood as the ultimate EOL. In other words, the material must be reused/ upcycled as many times possible before incineration to avoid the carbon from entering back into the atmosphere for a long time.

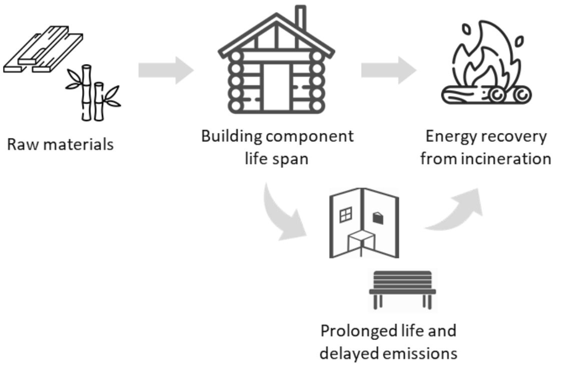


Figure 43: Delayed carbon emissions for maximizing carbon benefits (Source: Author)

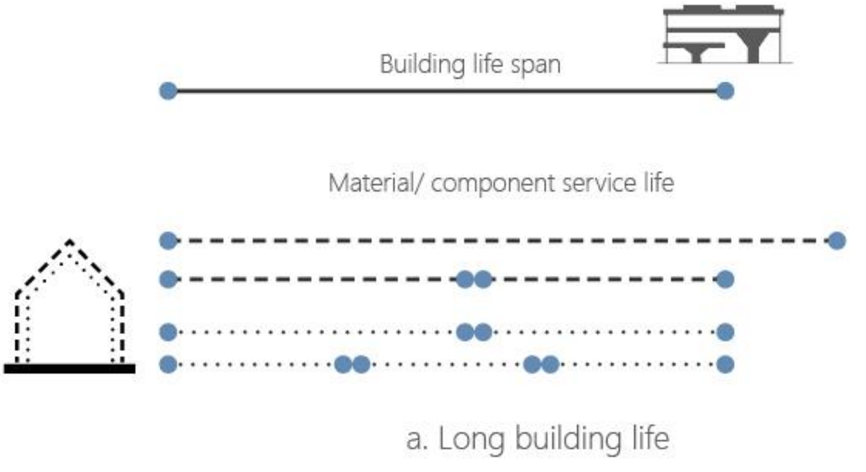
07 | Discussion

7.1 Interpretations

The findings from the analysis provide output values of carbon emissions in existing and proposed design. These values should not be interpreted individually as they are calculated using certain assumptions. However, the difference in results to interpret the impact on embodied carbon emissions remain precise. Some interpretations about life span of materials and their end-of-life are explained below.

7.1.1 Life span

Based on the assumptions in research, a comparison between two buildings- 120 years and 60 years life span were compared. The assumed number of years in assessment can be seen as representative figures to demonstrate two broad scenarios:



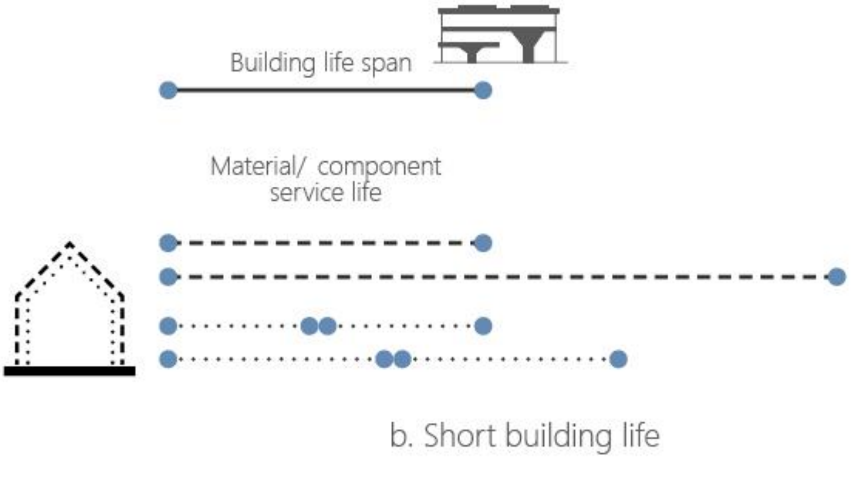


Figure 44: Two broad building scenarios with life span of different building layers represented by dashes/ dotted lines (Source: Author)

In Figure 44, the service life of different building layers are presented in dashed/ dotted lines to understand the suitable service life of materials. The materials with longest service life should be the suitable choice in both long building life and short building life scenarios. This would ensure reusability of materials even after the building life. However, there may be some alternate solutions where the material with shorter service life has significantly lower carbon footprint.

To address this challenge, a term $GWP_{1\ year}$ is derived for basic comparison between suitable materials. The $GWP_{1\ year}$ value would provide carbon footprint of materials per 1 year of their service life.

$$GWP_{1\ year} = \frac{GWP_{A1-A3} - ERP}{\text{Service life}}$$

where

$GWP_{1\ year}$	: Global warming potential (GWP) of material/ building component per 1 year of its service life
$GWP_{A1\text{-}A3}$	: Declared carbon footprint of A1-A3 modules ($kgCO_2eq.$/ total material quantity)
E.R.P.	: Energy recovery potential (if any from incineration) ($kgCO_2eq.$/ total material quantity)
S.L.	: Declared service life of material/ building component

The environmental impact of materials is most influenced by the $GWP_{A1\text{-}A3}$, service life and energy recovery potential. The rest of the life cycle stages (maintenance, demolition etc) are insignificant as compared to the $GWP_{A1\text{-}A3}$ and are also similar for different materials in most cases. The service life of materials is declared by the manufacturers and must always be taken into consideration while choosing materials.

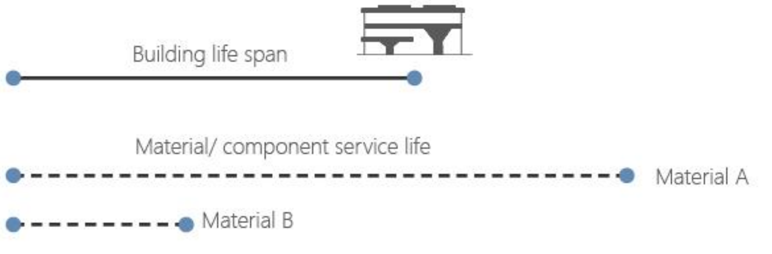


Figure 45: An example explaining importance of $GWP_{1\ year}$ value (Source: Author)

The importance of $GWP_{1\ year}$ is explained by an example (Figure 45) with two suitable material options for a building application. Material A and B are assumed to be equally feasible materials but with different service life and different carbon footprint. In such a case

If $GWP_{1\ year}$ of material A < material B, material A is preferred
Although if $GWP_{1\ year}$ of material B << material A, material B must be preferred

The other parameters (local availability and biogenic carbon stored) are also important while determining the material but do not have a lot of influence on the results. Materials with the closest proximity to the building site must be preferred to lower the transportation carbon emissions. The bio-based materials with highest biogenic carbon stored must also be preferred to increase the carbon stored in Technosphere.

7.1.2 End-of-life

The research to assess several end-of-life scenarios for materials was conducted for each building component. While the impact varied between the building components, the trend of best and worst end-of-life scenarios remained similar due to the common assumptions.

An example of results for beam is shown (Figure 46) comparing the $GWP_{1\ year}$ values of wood, steel and concrete including the end-of-life carbon emissions. The results are simplified to show the comparison of carbon footprint per year by assuming

- the service life of all the materials are 120 years
- the end-of-life for incineration/ recycle/ landfill occurs at 60 years
- the reuse scenario shows the materials being used until end of service life
- concrete with the lowest carbon footprint from research is shown

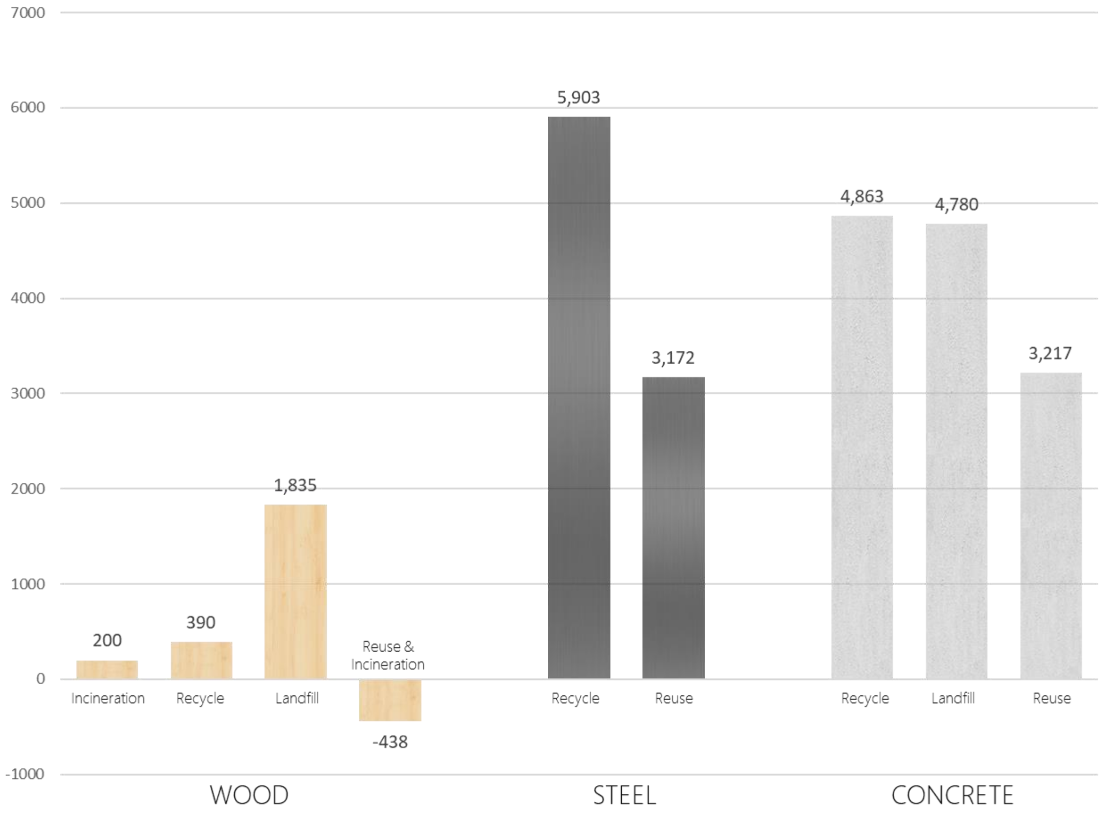


Figure 46: $GWP_{1\ year}$ values including different end of life of materials (Source: Author)

The results from above illustration are interpret as:

Bio-based material incineration and reuse: Incineration scenarios of wood, bamboo, wood fiber insulation, etc has the lowest carbon emissions. However, the use of such materials for longer period results in even lower carbon footprint as shown in 'reuse & incineration'.

Reuse and Recycle: In all the materials, reuse scenario results in almost half the carbon emissions as of recycle. This is due to energy intensive recycling processes that has higher carbon equivalent as compared to negligible carbon emissions involved in reuse.

Landfill: Landfill of wood presents higher carbon emissions due to release of carbon dioxide in soil. It is also an energy intensive process with almost no energy recovery and therefore, must not be practiced. Landfill of other materials such as concrete, PVC, etc. may also be harmful for the environment.

7.2 Advancing technologies in steel and concrete

In the literature research, some artificial sequestration method to produce concrete were studied. Some of these materials were still in research phase, while the others were commercially available in the market. Upon further research, product declarations of only few materials were found online. However, seemingly equivalent materials with the product declaration were also procured for the remaining materials.

The advancing technologies in concrete production are significantly reducing its embodied carbon footprint. Methods such as Carbon Capture and Storage (CCS) are adopted to capture carbon dioxide and use it in the curing process of concrete. Some other methods to reduce the quantity of Ordinary Portland Cement (OPC) in concrete are also adopted, as they are responsible for majority carbon emissions from concrete. These include use of Supplementary Cementitious Materials (SCMs) such as steel slag. While the product declarations currently available for new variants of concrete are able to account for the latter, they still have not managed to include the CCS benefits for concrete.

The analysis compared three types of ready-mix concretes- standard concrete, concrete with 20% SCM and a concrete variant with 100% replacement of coarse aggregate (from Van Nieuwpoort Groep). Based on available literature on carbonation of concrete during its lifetime, the carbon benefits were calculated and credited in this research. The EOL scenario of recycling concrete was also calculated and credited in the assessment. The results for these three types of concrete clearly indicated reduced impacts on the carbon footprint. Along with the advancement in technology for concrete, increasing recycled content of steel was also studied.

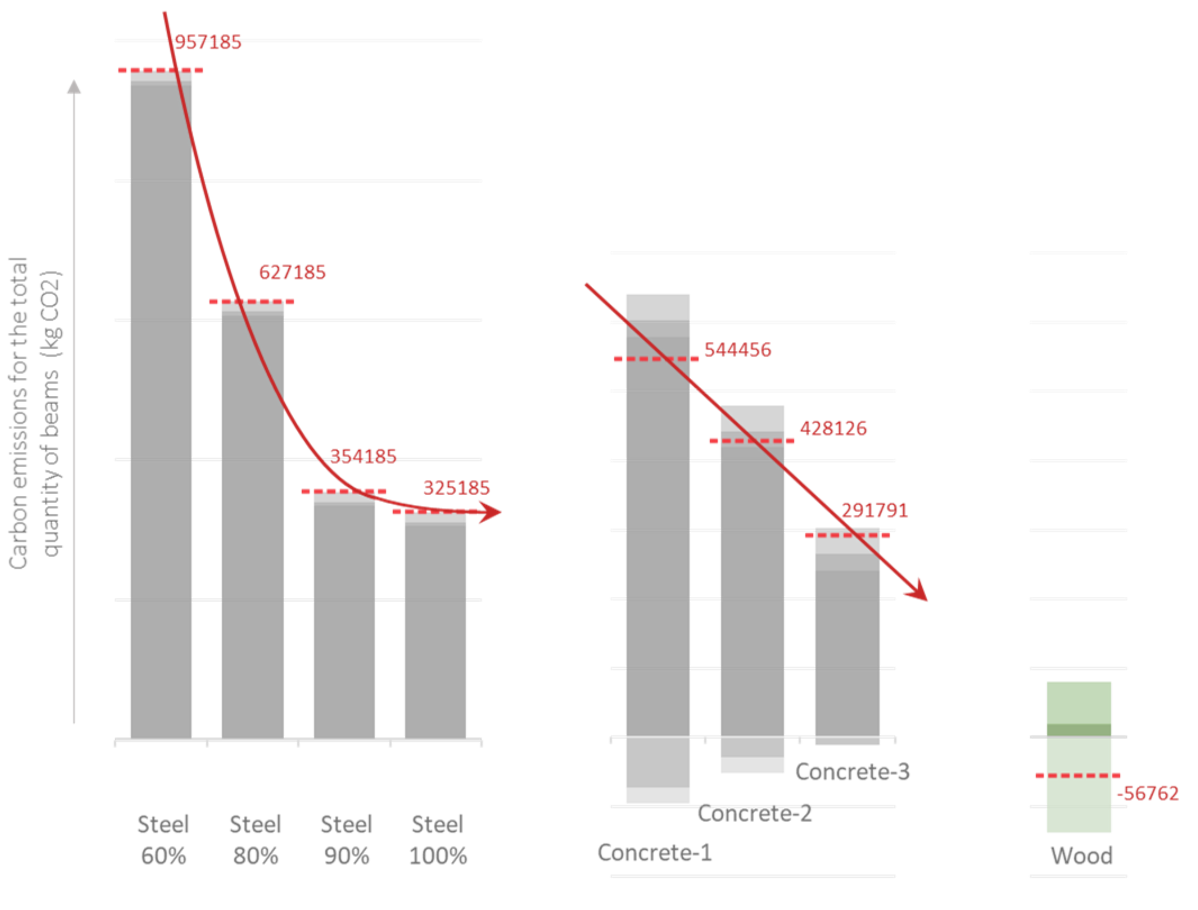


Figure 47: Improvements in steel and concrete production highlighted and compared with the carbon emissions of wood (Source: Author)

Figure 47 shows the trend of reducing carbon emissions with material advancement. The bar chart uses the example of material quantities required for beam in the Echo building and scenario 120_RC for concrete and steel. The increased recycled content of steel from 60% to 100% over the years has shown an exponential impact on the reduction of carbon emissions. On the other hand, the three types of concrete studied in the report also show a linear reduction. However, both the materials currently have much higher impact than the use of wood in scenario 120_I.

A research by Nässén, Hedenus, Karlsson, & Holmberg (2012) has also considered a future scenario where the CCS methods can capture 80% of the carbon emissions from steel and concrete industry. This scenario was compared with wood, where CCS technology is also used in the incineration process at its EOL. The resulting comparison also confirms the advantage of using wood over concrete and steel in construction.

It can, therefore, be concluded that the ***hypothesis of using artificially sequestered concrete products as building material to achieve lower impact than conventional wood products has been disproved.***

7.3 Applicability and impact upon changing variables

7.3.1 Application in other new/ existing projects

The assessment method used in the report is adapted to include the circularity aspect, material quantities, and carbon sequestration. Therefore, the results show an overall impact of the case example studied, i.e. Echo building in TU Delft Campus. It was essential to analyse and compare the total material quantities used in building components to understand the overall impact caused by the building.

The results from this research ***may be used as a basic benchmark*** for embodied carbon emissions to compare with other projects. The results are totalled for the super-structure, façade and façade awnings to provide an estimated carbon footprint per square meter of built-up area.

Proposed design: Embodied carbon emissions of super- structure, façade, and awnings = (-61.8-56.8-208.6+186.4+14.9) x 1000 / 8800

= -125900/8800 = ***-(minus)14.3 $kgCO_2/m^2$***

The calculated value for existing design was 203.5 $kgCO_2/m^2$, which is validated by checking estimated results of other researches. A research by Wolf (2017) concludes by estimating the carbon footprint of SMQ (Structural material quantities) per square meter of built-up area to be between 200-550 $kgCO_2/m^2$. However, scope of building materials in her research also included foundation and roofing.

Assuming a similar scale building uses the same amount of materials in construction, the calculated value of –(minus) 14.3 $kgCO_2/m^2$ can be multiplied by the built-up area. This shall provide a rough estimation of the resulting environmental impact from the super-structure, façade, and awnings between two types of construction.

Other type of constructions such as existing projects, high-rise construction may also use the assessment method to derive project-specific results. A ***design guidelines manual*** explaining step-by-step approach to assess and evaluate suitable materials for a low carbon construction is added at the end of this report.

7.3.2 Impact on results by changing the variables

The research conducted in this project uses some assumptions that may influence the results. These variables may be changed based on the scope of assessment.

- *Life span of 120 and 60 years:* The buildings must be assessed for their whole life span. This also includes the replacement of other building components at their end-of-life. However, the structures with shorter life span would have different results for building components that are replaced.
  An example of façade assessment is shown in Figure 48, where the life span of analysis was reduced from 120 years to 30 years. The figure shows change in carbon emissions at each life stage and the combined impact on results. The PVC frame windows show lower carbon emissions than wood-aluminium upon change of variable due to change in number of replacements.

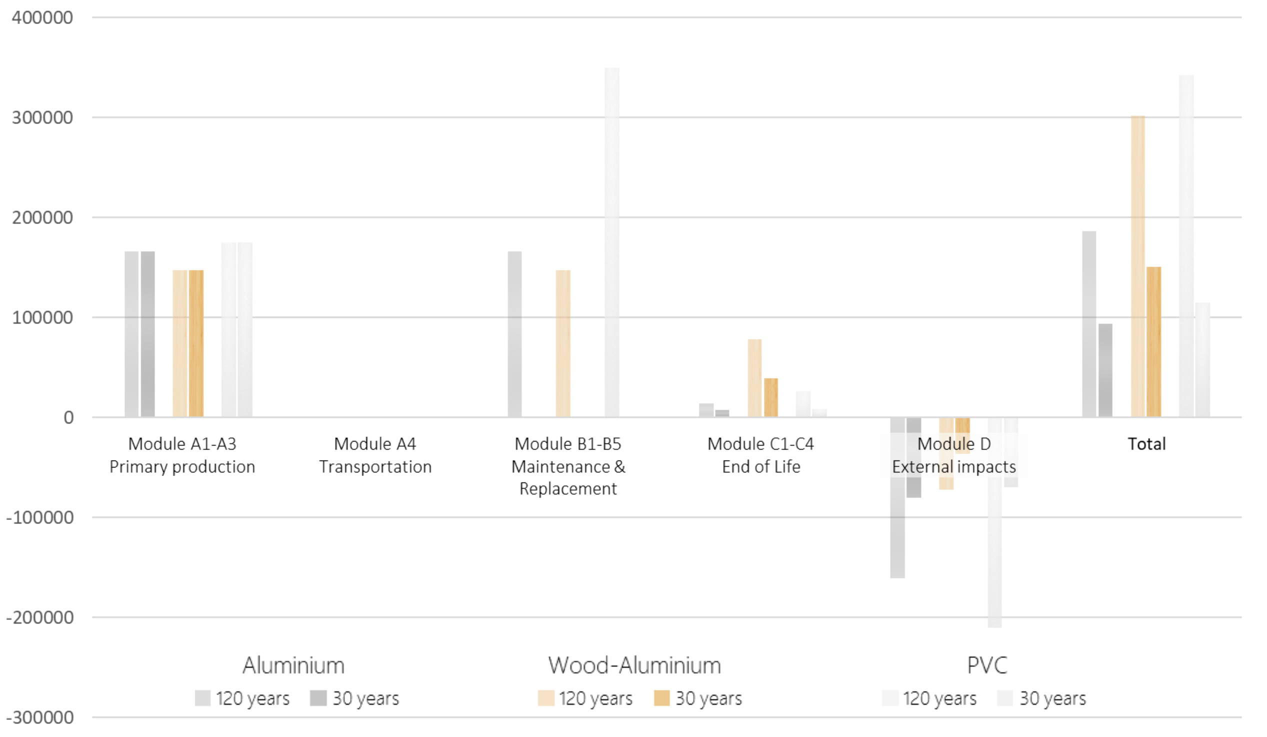


Figure 48: Assessment of facade with change in life span from 120 years to 30 years (Source: Author)

- ***Different material source:*** The module A1-A3 is significantly impacted upon changing the material source, i.e. manufacturer and country origin. Different countries have varying policies related to recycling materials or management of forests. This also results in change of transportation emissions (A4), but the impact is insignificant. The overall change may result in either increasing or decreasing the embodied carbon footprint of materials. Figure 49 shows an example of the impact upon changing material source in assessment of beams. A steel with lower percentage of recycled content, wood with lower carbon sequestration and concrete with lesser SCM percentage is selected to show the worst scenarios possible, because the old analysis already assumes near-positive scenarios. The results in case of structural components indicate that wood remains the lowest carbon footprint material.

- ***Different energy recovery potential:*** The energy recovery potential upon incineration of bio-based materials also differs between different companies and countries. A range of 200-500 $kgCO_2/m^3$ energy recovery potential was observed from different data procured from Australia, UK and EU. Figure 49 shows an example of the impact upon lowering the energy recovery potential of wood incineration. The altered results may cause the wood to indicate positive carbon emissions, but still the difference between wood and other materials remain substantial.

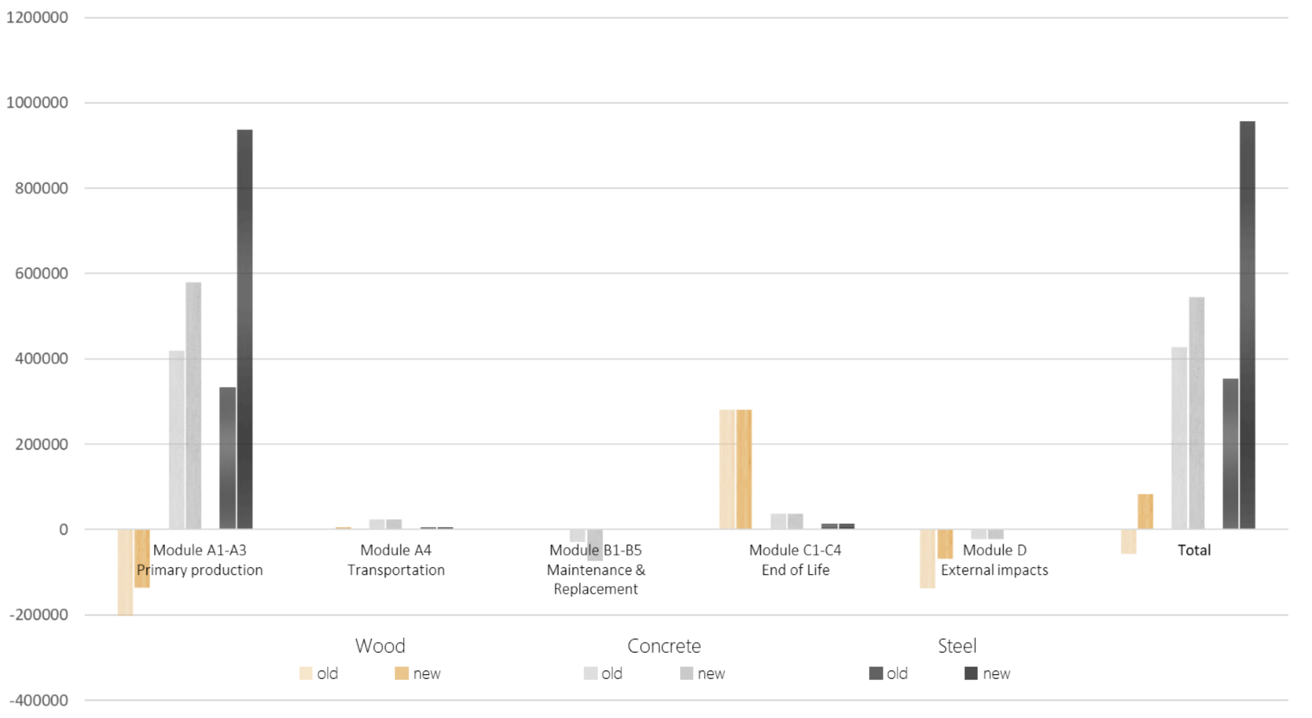


Figure 49: Impact of changing variables on assessment of beams (Source: Author)

The buildings may also be studied with different assumptions based on other literature resources. The difference in assumptions may lead to varied results, which also forms a part of further research on this subject. Some of the assumptions may be added in this research are:

- ***Upcycling as an end-of-life scenario:*** This would require a defined use of upcycled material and carbon emissions involved in the process. Better results for concrete can be expected from this scenario as lower energy consumption is anticipated.
- ***Energy recovery as ultimate EOL for wood:*** Wood products can be given more credit upon having upcycling/recycling as the EOL scenario. If the wood product is assumed to ultimately incinerated after upcycling/recycling, a method to give credits could be formed to prolong the carbon stored in the built environment.
- ***CCS potential:*** The EPD data does not currently give credits for CCS at production or disposal stage. An assumption based on the impacts of other industries could be made to give credits for CCS methods. However, precaution must be taken such that the benefits are not accounted twice in different industries.
- ***Building life completing its carbon debt:*** An important discussion among the LCA practitioners is whether the debt of stored carbon in building materials can be considered nullified after 100 years.

7.4 Limitations of the research

Some limitations of the research are:

1. The research focused only on the Global Warming Potential (GWP) indicator of the building materials, i.e. CO2 equivalents of Greenhouse gases. It does not consider other impact indicators such as acidification, eutrophication potential etc.
2. There are limited number of materials studied in the research representing broad material families. Thus, the interpretations do not include the materials out of scope from research.
3. Alternate materials proposed in the guidelines have equivalent structural properties. However, other properties such as thermal or acoustic are not considered but attempted to be similar.
4. The use of alternate materials may cause a consequential need for other solutions, such as fireproof coating or heavier scaffolding. Therefore, reassessment of design while detailing could lead to more accurate results.
5. The demonstrated end of life scenarios are assumed to have 100% conditions of incineration/ reuse/ recycle/ landfill. However, due to limited technology, the current practical conditions do not allow that.

The research is based on several assumptions and data from different literatures. There may be some gaps in the assessment method, which would improve with the development of LCA in building industry. However, the assessment method and results are robust enough to include findings from future studies or adapting the variables to different analysis.

08 | Conclusions and Future work

This research aimed to study and compare the impact of embodied carbon emissions of building materials to propose solutions that can help achieve zero carbon goals. The conventional life assessment method was found unsuitable to analyse advancing materials based on the contemporary circular approach to design. Therefore, the assessment method was adapted using certain assumptions and scenarios to compare both materials and their end of life.

The literature research was conducted to report advanced building materials such as carbon cured concrete, carbonated aggregates to reduce cement quantity, and hempcrete. Types of wood were also identified to understand their application in construction. Module-A carbon emissions of LCA was obtained from third-party verified EPDs for most of the materials. The data for other modules was partly assumed using EPD information provided by some materials and partly by literature research. Structurally equivalent material quantities for different building components (i.e. columns and beams) were manually calculated using thumb rules derived from literature and analysis. With the proposed assessment framework, the building components were analysed using different materials in various scenarios.

After answering the sub-research questions related to the proposed assessment method and available material options for comparison, analysis of each building component was done to answer the main research question:

"What alternate materials and strategies can be used in building design that can lower the embodied carbon footprint to meet zero carbon goals?"

The results from analysis of Echo building concluded that **bio-based based material solutions (i.e. Glue laminated wood for columns, planed timber beams, CLT slabs, bamboo for façade awnings, and wood fibre insulation material)** showed the maximum potential in reducing the carbon emissions of the building. Since wood-frame façade option was not assessed against aluminium façade due to its unavailability in current construction industry, there was not a better solution found for the façade design (aluminium frame). In all the former material options, the associated end-of-life scenario was proposed to be **incineration with energy recovery**. The proposed materials were found to have slightly lower carbon emissions when used in a longer life span building (i.e. 120 years) than a circular building (i.e. 60 years). Other strategies are further explained in the design guidelines. The proposed material and scenarios were found to have net negative carbon emissions, i.e. removing more carbon dioxide from atmosphere than emitted.

The overall impact in reducing the carbon emissions of Echo building was estimated to be around 120%. This translates into a **reduction of almost 1900 Metric tons of CO_2 ($MtCO_2$ eq.)**. While the carbon emissions from structural elements of Echo building are expected to be offset in 24 years using the renewable energy of building, the proposed materials anticipate a carbon-negative structure with a potential to bring down this offset period to minus (-) 5 years (refer to Figure 41).

A **hypothesis** of achieving zero embodied carbon emissions using biological or artificial method was proposed. The results discussed above for biologically sequestered carbon in wood and bamboo **partially proves the hypothesis.** However, the artificial methods used for concrete to store carbon **disproves the other part** of hypothesis. The trend in material advancement for concrete and steel was tested against the carbon footprint of bio-based materials. It was noted that there is still a stark difference between their net carbon emissions.

Future work

The life cycle assessment is gaining more attention over the years. With more research and developments being done on LCA, the method is getting more integrated with the design approach. However, more collaboration between the LCA practitioners, policymakers and other stakeholders is required to raise awareness about making carbon-conscious design decisions. Further research on some topics mentioned below may benefit this collaboration and LCA development:

- More data on the circular buildings is needed to allocate accurate carbon emission values for module C and D. The circular building concept is relatively new. Thus, there are no practical studies that measure energy consumption from disassembly process, sorting, and storing process, quality check and reshipment to the construction site. Further research on LCA of circular buildings would incentivize the architects and designers to showcase their design or compare them with benchmarks.
- Some research on material passport is already underway. To support this, more research on how to integrate them better with LCA must also be done.
- The LCA results must be applied at an early-design stage of new projects. To facilitate this, concise results of hotspots can be used to guide the concept design. A better technical infrastructure for LCA and software is needed to boost the process.
- EPDs currently serve as the most reliable source of product information. However, they cost a lot to the companies opting for it resulting in a limited database. More incentives can be given to declare products and build a bigger database.
- The assessment method in this report has studied only selective materials for few building applications. Using the method explained in section 7.1, more materials can be studied to build up this database.
- From this research, it was realized that some specific building applications such as façade and insulation material also lack data regarding the carbon emissions from replacement, maintenance, and demolition. A digital method to record the energy consumption and carbon emissions would immensely benefit the LCA calculations.

The research has highlighted the importance of carbon assessment for buildings. A separate role of carbon designer is expected to catch more attention over time. It may even be integrated with an existing role of climate designer or building manager. A key takeaway for the department of Architectural Engineering and Technology (AE+T) in Bouwkunde faculty of TU Delft could be to integrate such courses in the academic curriculum or to introduce such roles in courses like MEGA.

09 | Relevance

9.1 Novel approach for the life cycle assessment

The life cycle assessment method was introduced long ago for all kind of products and processes. New standards have now been introduced to adjust this assessment method for buildings to calculate their impact. Due to the increased complexities involved in the assessment method, the practice of conducting LCA has also become another specialization. This has resulted in a more significant gap between the architects and LCA.

While the need to include all relevant factors in LCA calculation is acknowledged, the assessment method must also become more transparent and concise for non-LCA practitioners. This is proposed to raise awareness among the architects and designers about the growing importance to address the embodied carbon emissions. Factors such as carbonation of concrete, emissions from disassembly process and energy recovery potential are addressed in this report to assess the whole building life cycle. The proposed assessment method aimed to integrate circularity aspect with the traditional LCA method.

The impact of building materials spans much more than just cradle-to-gate carbon emissions shown in EPD. The materials need to be evaluated with the building context to understand the actual impact of real quantities in actual situation. This report uses the proposed assessment method to analyse and compare certain building materials in their application to understand their impact. Although the approach adopted in this report is case-specific to the building examined, the results may be used to define hotspots in life cycle modules of building elements. These hotspots could be used to provide elementary calculation for design at an early conceptual stage.

9.2 Role of policy makers, stakeholders, and academia

The life cycle impact of building materials in a circular approach, as studied in this report, is also being discussed in other forums. One of the shortcomings in this system is lack of collaboration between the LCA practitioners of such forums and other stakeholders. While the academicians are more involved in such development, the stakeholders continue to follow business-as-usual ideology. The product declarations and benchmarks are produced for greenwashing and to benefit themselves. This creates a more susceptible environment for architects and designers to fall prey of unsustainable practices.

The policymakers and stakeholder must work in collaboration to support the idea of circular economy. By providing incentives and more resources for further research on this subject, new tools may be developed that can help boost the design practices towards sustainability.

The scientific community can contribute to this by funding more research projects in this subject. The LCA method is continuously evolving to adapt with the everchanging construction industry. More research projects on how to integrate module D benefits to incentivise circular design practice can be done. This report has successfully attempted to study 100% of different end of life scenarios to highlight their impact. Although the approach taken may be impractical, it intends to influence the stakeholders to move towards the right path.

9.3 Importance of bio-based materials in climate change mitigation

The forests serve as natural sink for carbon emissions to store biogenic carbon in trees and plants. This process of carbon sequestration allows enormous quantities of carbon to be stored as biomass in materials. The UK Committee on Climate Change (2018) has released a report stressing over the shift of economy to biobased solutions ranging from industrial use to biofuels in aviation. In this report, the importance of using bio-based materials in construction industry has been highlighted particularly. The use of harvested biomass (i.e. bio-based materials) in construction industry has the potential to sequester carbon dioxide from the atmosphere and be stored for prolonged periods before being used as an energy source.

An example of a building with 120 years lifespan can be taken to understand the benefit of stored biogenic carbon. It is assumed that a tree takes about 40 years to reach maturity and sequesters carbon at a lower rate after that. The forests may also be vulnerable to wildfires or storms eventually, adversely causing more carbon emissions into the atmosphere. However, when the biomass is harvested at maturity and locked into building materials for an extended period, say 120 years, three new growth cycle of trees can sequester thrice as much biogenic carbon into the Technosphere.

The assessment of materials in this report using a cradle-to-cradle approach concludes by proposing bio-based materials for every building element possible. The results reported in section 7.2 goes beyond the current practice of assessing other materials such as concrete and wood to see their future potential in reducing carbon emissions. In all the future scenarios considered, bio-based materials are seen to have much lower impact than the other materials. They even show potential to achieve negative carbon impact on the atmosphere by using efficient energy recovery methods at the end of life.

The benefit of using bio-based materials to lower the carbon footprint of buildings would be much higher if the product is reused/ upcycled. This would allow the biogenic carbon to be stored in the Technosphere for extended time. However, this would pose accounting challenges to the LCA practitioners as this benefit will have to be distributed among more life cycles of recycled products. Another common assumption made in the conventional LCA practice is the carbon neutrality of forests. As much as this reduces the complexity of LCA, it could also lead to harmful impacts to the environment. Therefore, the carbon burdens from previous life stage of bio-based materials must be declared and accounted in the total calculation of carbon footprint.

The underlying question from this discussion remains: Whether there is enough wood to support the biomass economy? Some countries like Sweden, Russia and UK are making efforts to increase their forest growth and dependency on biomass remarkably. The wood used in construction in most of the European countries are produced from sustainably managed forests. However, the growing demand of wood from all industries may soon pose a challenge to the forests.

10 | Reflection

As the construction industry is moving towards energy-efficient buildings, the operational carbon emissions of the project decreases but the embodied emissions due to building materials increase significantly. Many building councils, including the World Green Building Council (WGBC), are now focusing on the goal of zero-carbon buildings, including the embodied carbon. However, due to the complexity of carbon footprint calculation for a whole building, the definition of 'zero-carbon' is still unclear and inconsistent among different organizations.

As much as the goal seems far-fetched, there has been some progress in bringing down the carbon footprint of buildings using low carbon materials, such as timber, bamboo, and hempcrete, or designing the building using circular design strategies. But due to the much-debated evaluation method of Life Cycle Assessment (LCA), it is difficult to understand the true carbon footprint of a building. The graduation thesis presents a comparative analysis of materials based on their embodied carbon emissions. The research objective was to propose low carbon building materials in a new building depending on different scenarios. The thesis intends to conclude by presenting these material solutions for an upcoming building in TU Delft, i.e. Echo, and as guidelines for other new or renovation projects.

This graduation thesis has been remarkably ***helpful in expanding my horizons of understanding*** about many aspects of the built and natural environment. The research required a thorough grasp of forest management, carbon flows in the environment, material production methods, and end-of-life scenarios of building materials. The research and conclusions from this thesis would help me make critical decisions in my professional life ahead.

Aspect 1: Elaboration on research method and the results

The LCA method has some shortcomings, such as neglecting end-of-life carbon emissions, neglecting biogenic sequestered carbon, and the inability to account for cradle-to-cradle approach. Several other approaches to LCA exist that try to address the problem of time-based calculation method. However, none of them stand unopposed by other experts in the field. As the traditional LCA method is widely adopted across the building industry and was comparatively easier to learn, the graduation thesis uses the same for analysis.

Environmental Product Declarations (EPDs) provide part information of the LCA for building materials, verified by third-party organizations. They are getting more and more popular among architects and engineers now. As EPDs are believed to provide reliable information, the graduation thesis makes use of the data from available EPDs for some materials. Other materials that do not have an EPD are assessed using the existing literature.

Due to the limitations of an LCA method, a self-derived assessment method had to be established. The research method makes use of an online tool 'One click LCA' to input the basic information about the building. The tool has a huge database of EPDs, allowing it to produce reliable results. Parameters such as the lifetime of a building, recycled percentage of materials, and location-based transport emissions are used in the software. The results from the software are then analysed based on different scenarios for the building. These scenarios include different end-of-life scenarios, different building lifetime, and impact from the sequestered carbon.

The described research method was ***successful in producing reliable results***. The One Click LCA tool has been quite useful to generate results. Furthermore, feedback from my mentors over the interpretation of results and relevance of the thesis in scientific community has been extremely helpful in shaping the conclusions. With their constant input on the analysis, careful interpretations were made from the results. Chapter 8 suggests some further research on LCA analysis that would greatly help to achieve more accurate results.

Aspect 2: Relationship between research and design

The graduation thesis aims to present the impact of different materials and scenarios on the carbon footprint of a building. The research mainly takes into account the structural design of the building to propose alternate materials in construction. The results thus presented are aimed to guide the existing design of the Echo building.

The CRE (Camus and Real Estate) department of TU Delft could apply the learnings from this graduation thesis in the upcoming Echo building project for the pending design decisions. They could also use the results and conclusions into other future projects of TU Delft, right from the conceptual phase. The presented outcome in this thesis highlights the importance of using bio-based building materials. It even shows the possibility of achieving a carbon-negative structure that may ***contribute towards the zero-carbon goals of TU Delft campus.***

Aspect 3: Placing the graduation topic in the Building technology (BT) track and Master program (MSc AUBS)

The building technology track includes different disciplines, i.e. Climate, Structure, Façade, and Computation, all of which allows the students to explore building design using different materials. Some of the studios also teach us to assess the comfort and energy parameters of building design. However, the track doesn't give us much opportunity to delve into the ***carbon footprint calculations*** of materials or a building. As these calculations are widely taught in the Industrial Design (IO) department, guidance was sought from Prof. Joost Vogtländer, an expert on LCA from the IO department of TU Delft.

Secondly, it was realized that the Bouwkunde (BK) faculty and the Building Technology (BT) track are slightly limited to ***research on conventional materials.*** Many studies on methods of carbon sequestration in concrete were found from the Civil Engineering and Geosciences (CEG) department on the repository of TU Delft. In the BK faculty, the conventional ideas of using wood as a building material seem to overshadow the possibility of exploring the design strategies using other materials. The graduation project is also strongly connected to the circular design strategies for building construction. Thus, guidance from Bob Geldermans, a Ph.D. researcher on the circular built environment, was taken to mould the thesis research such that it addresses the circularity principle as a key component.

The role of carbon designer is expected to gain more importance in the architecture industry. If more graduation projects on this subject are expected from future candidates of BT track, it would be helpful to ***introduce a role of carbon designer*** in courses like MEGA or have similar ***courses integrated into the academic curriculum.***

Aspect 4: Elaboration on the relationship between the graduation project and the wider social, professional and scientific framework, touching upon the transferability of the project results.

The graduation project aims to bring awareness about imminent problems for net-zero buildings and propose solutions based on the on-going researches in the market. The goal is to influence the design process in upcoming buildings of TU Delft campus to achieve carbon neutrality by using low embodied carbon materials. The conclusions would also ***influence the larger audience in the architecture industry*** to shift towards environment-friendly material options for construction gradually. As zero carbon buildings are upcoming goals of the building councils, more architects are expected to shift towards such design principles gradually.

The research studies limited materials and shows a comparison based on a self-derived assessment method. Further studies could use the assessment method, as explained in the report, to analyse more materials or other building components. Some gaps, such as disassembly and construction energy needed in circular buildings, could also be researched to improve the accuracy of results.

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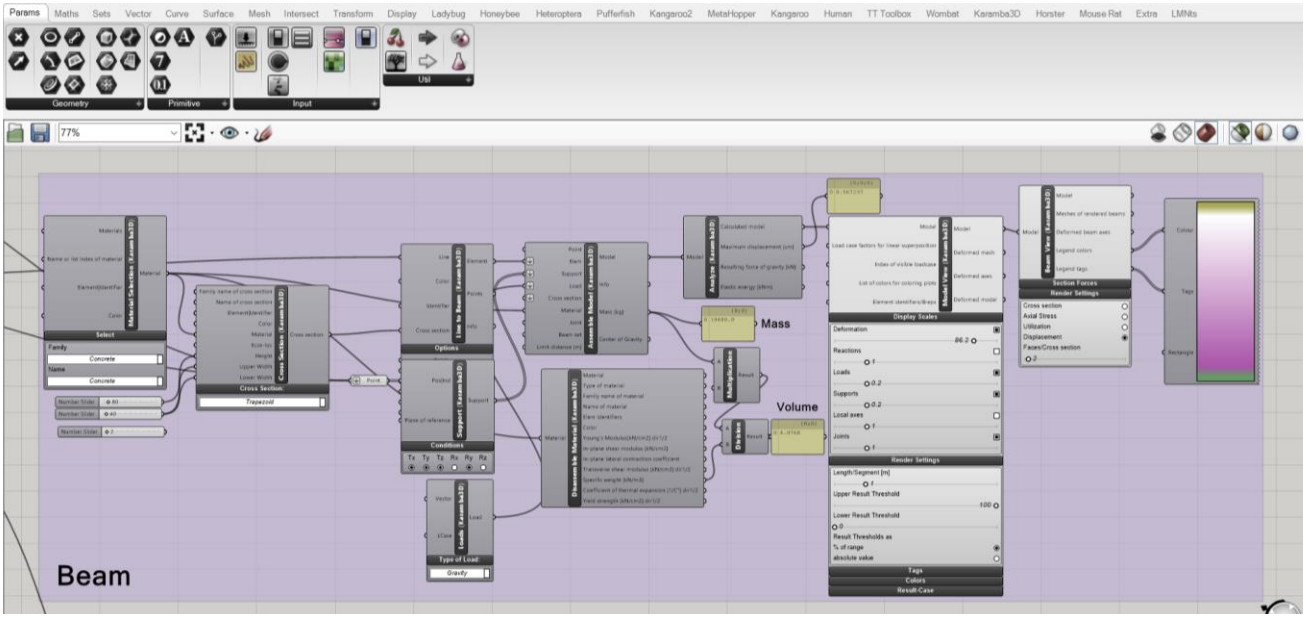
Yang, K. H., Jung, Y. B., Cho, M. S., & Tae, S. H. (2014). Effect of Supplementary Cementitious Materials on Reduction of CO2 Emissions From Concrete. In *Handbook of Low Carbon Concrete*. https://doi.org/10.1016/B978-0-12-804524-4.00005-1

12 | Appendices

12.1 Determining material quantities



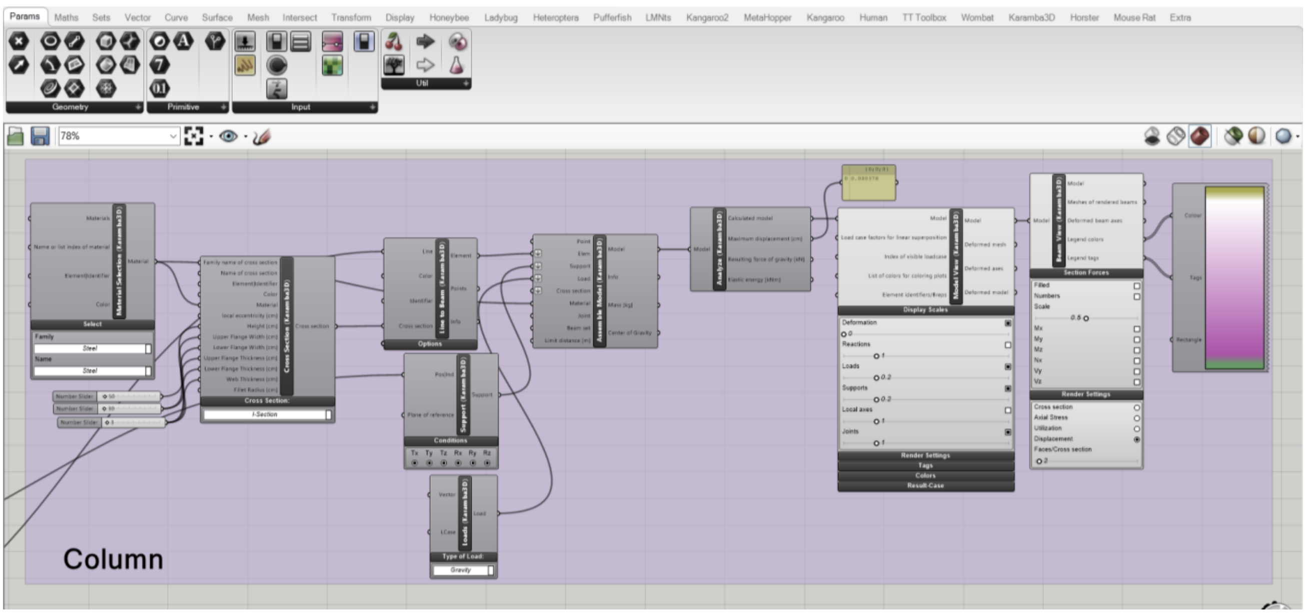


Figure 50: Karamba3D tool used to test deflection in structural members with different materials

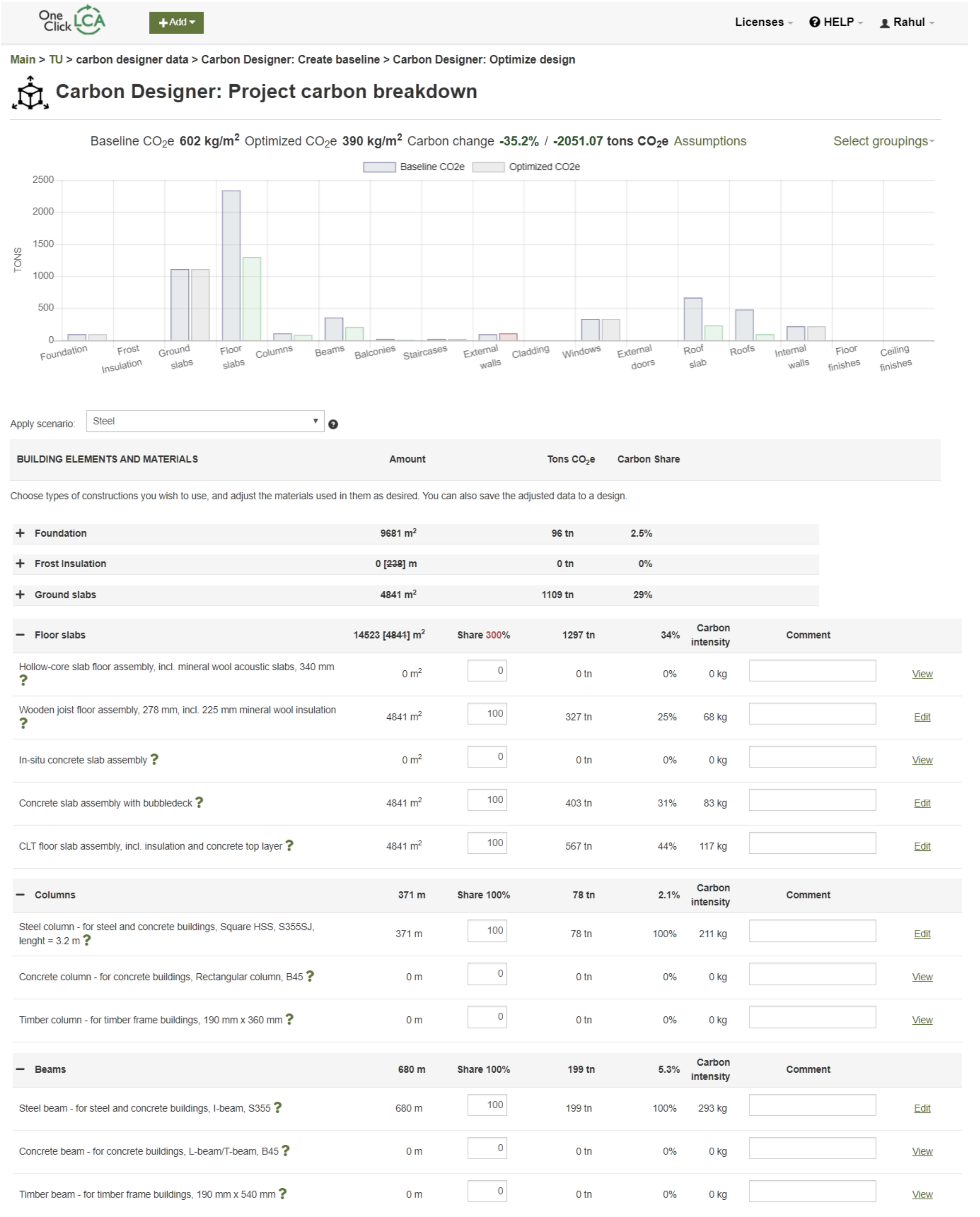
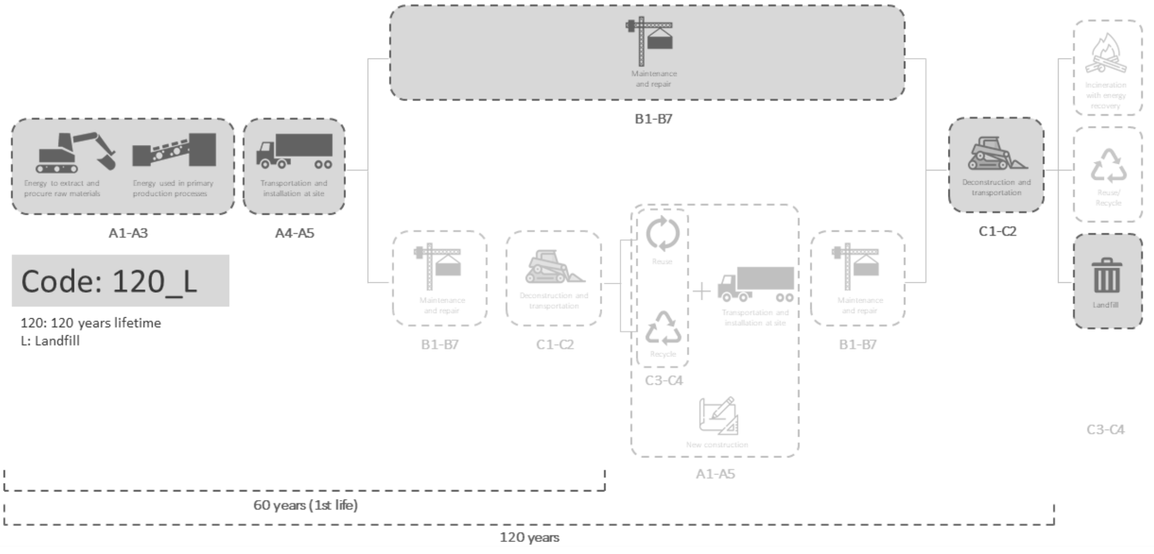


Figure 51: Carbon Designer tool in One Click LCA showing different material options for a same required built-up area

12.2 General scenarios for materials as a specific structural element



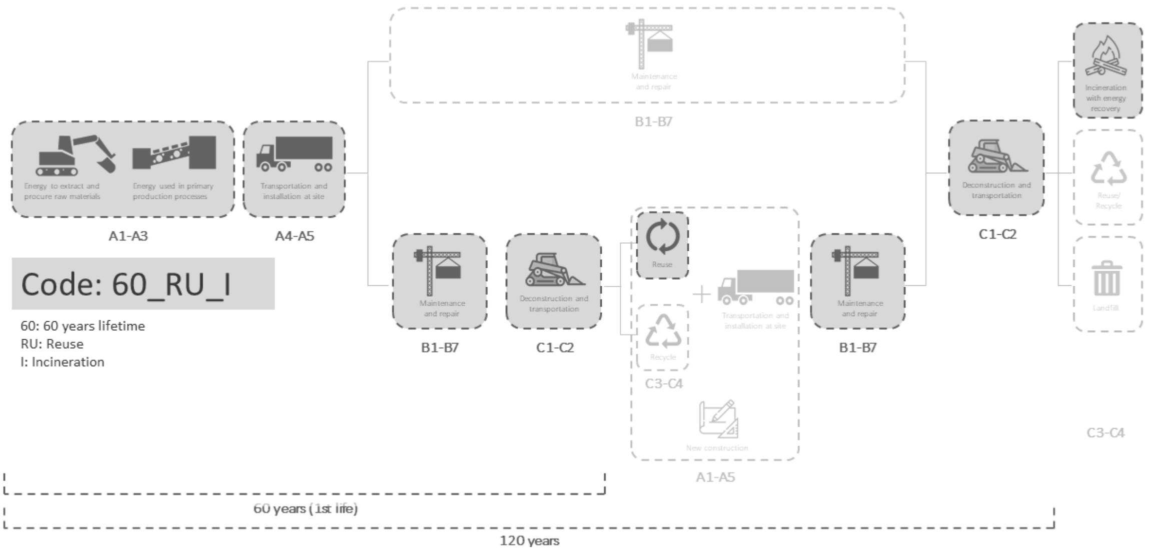
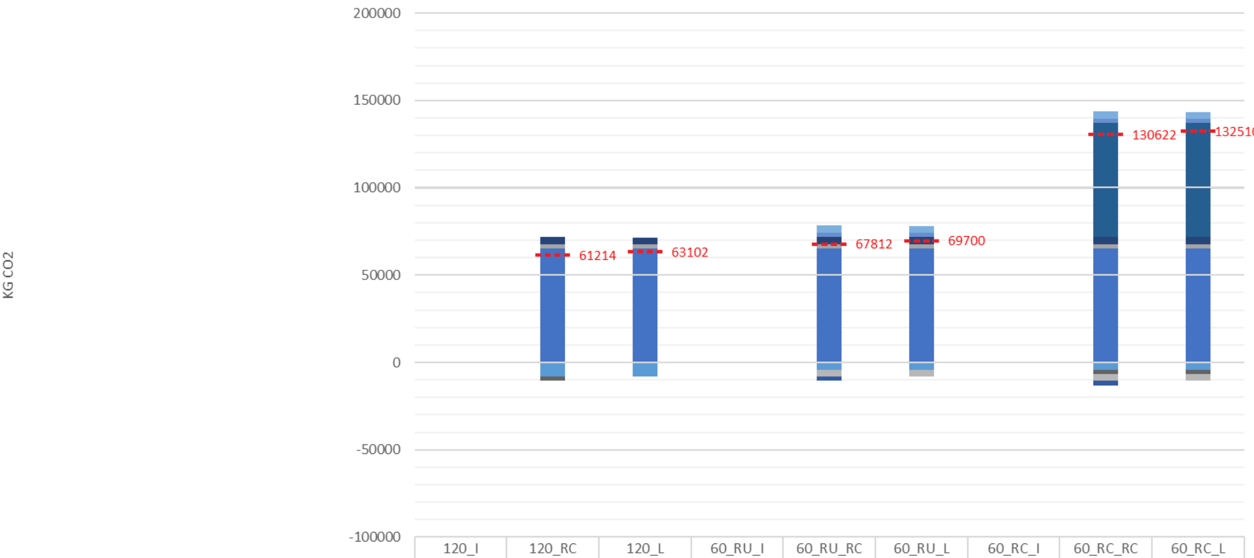


Figure 52: Examples of two scenarios as explained in Section 5.4 (Source: Author)

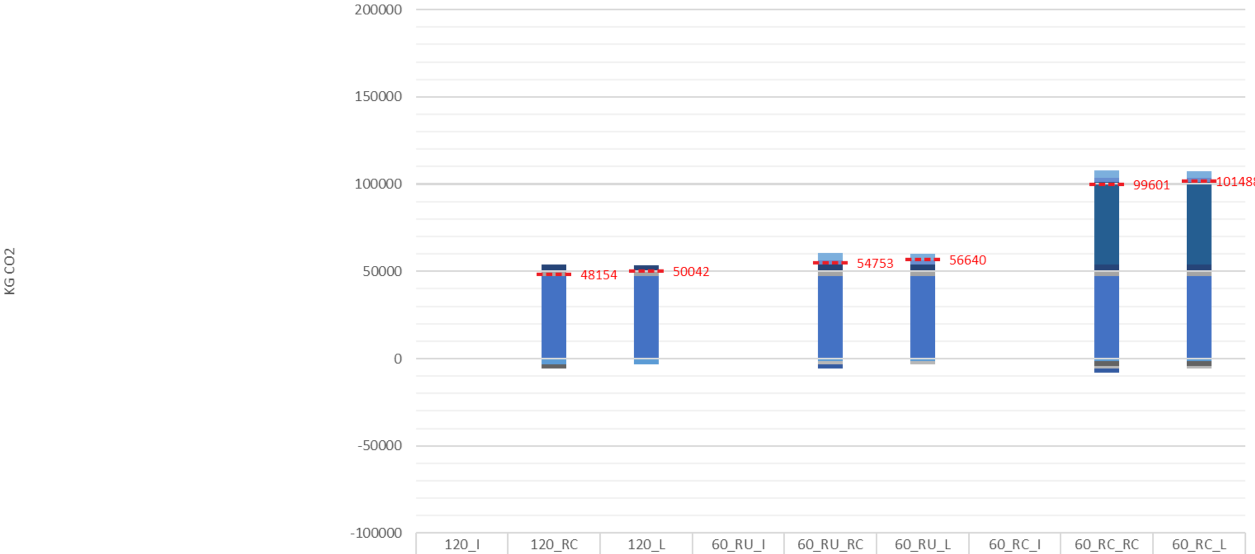
12.3 Life cycle analysis

12.3.1 Material options and their scenarios for columns



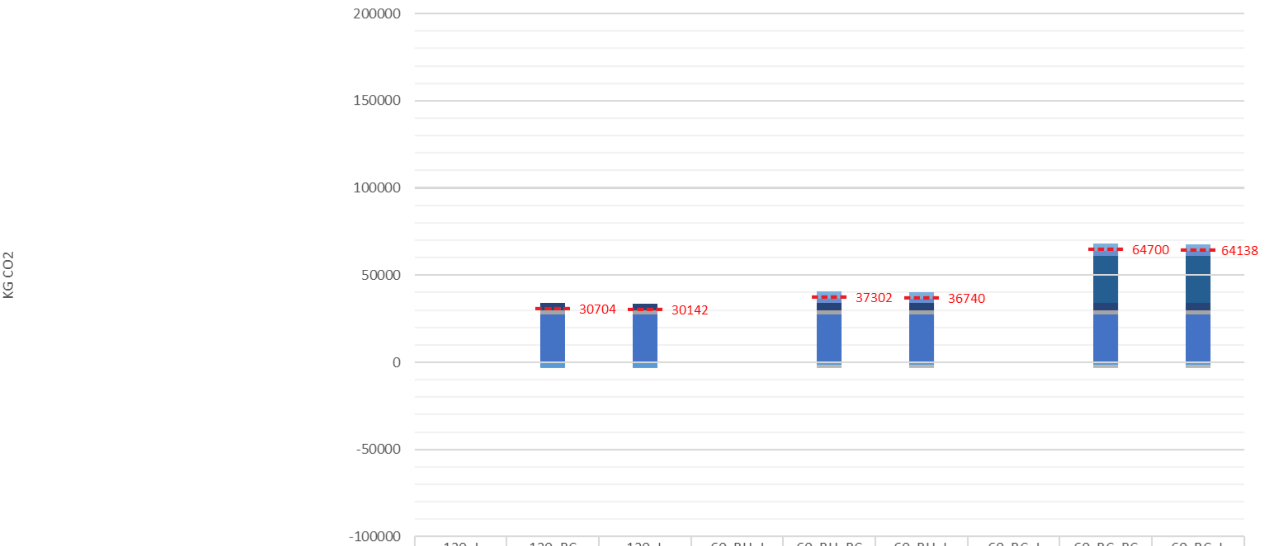
	120_I	120_RC	120_L	60_RU_I	60_RU_RC	60_RU_L	60_RC_I	60_RC_RC	60_RC_L
Second Life External Impacts (D') *can't take this into account					-2450			-2450	
Second Life End of Life (C1'-C4')					4167	3605		4167	3605
Second Life Maintenance and replacement (B1'-B5')					-4097	-4097		-4097	-4097
Second Life Transportation (A4')					2629	2629		2629	2629
Second Life Primary Production (A1'-A3')								65062	65062
First Life External Impacts (D) *A5 not included		-2450						-2450	-2450
First Life End of Life (C1-C4) *A5 not included		4167	3605		3969	3969		4167	4167
First Life Maintenance and replacement (B1-B5) *A5 not included		-8194	-8194		-4097	-4097		-4097	-4097
First Life Transportation (A4) *A5 not included		2629	2629		2629	2629		2629	2629
First Life Primary Production (A1-A3)		65062	65062		65062	65062		65062	65062

Figure 53: Standard Concrete (including the carbonation during lifetime)



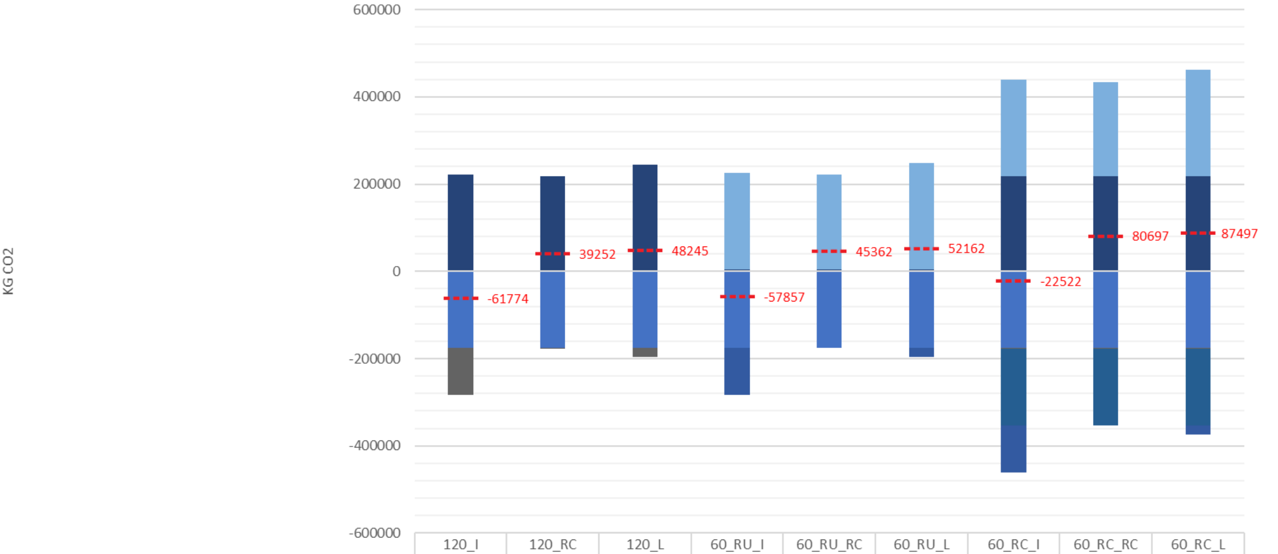
	120_I	120_RC	120_L	60_RU_I	60_RU_RC	60_RU_L	60_RC_I	60_RC_RC	60_RC_L
Second Life External Impacts (D') *can't take this into account					-2450			-2450	
Second Life End of Life (C1'-C4')					4167	3605		4167	3605
Second Life Maintenance and replacement (B1'-B5')					-1646	-1646		-1646	-1646
Second Life Transportation (A4')					2629	2629		2629	2629
Second Life Primary Production (A1'-A3')								47100	47100
First Life External Impacts (D) *A5 not included		-2450						-2450	-2450
First Life End of Life (C1-C4) *A5 not included		4167	3605		3969	3969		4167	4167
First Life Maintenance and replacement (B1-B5) *A5 not included		-3292	-3292		-1646	-1646		-1646	-1646
First Life Transportation (A4) *A5 not included		2629	2629		2629	2629		2629	2629
First Life Primary Production (A1-A3)		47100	47100		47100	47100		47100	47100

Figure 54: Concrete with SCMs (including the carbonation during lifetime)



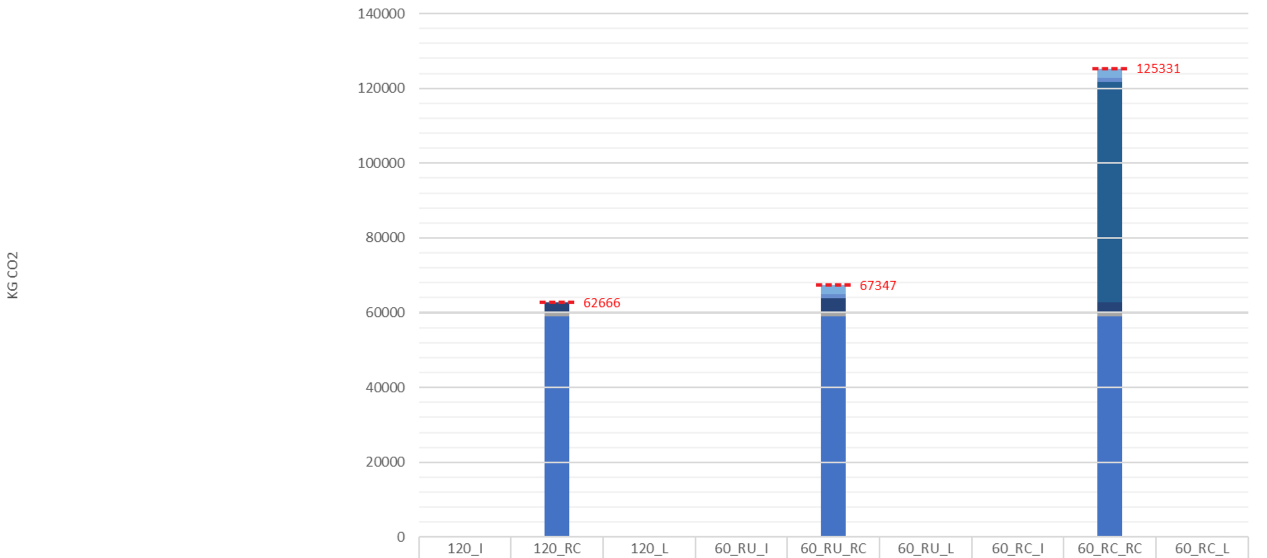
	120_I	120_RC	120_L	60_RU_I	60_RU_RC	60_RU_L	60_RC_I	60_RC_RC	60_RC_L
Second Life External Impacts (D') *can't take this into account									
Second Life End of Life (C1'-C4')					4167	3605		4167	3605
Second Life Maintenance and replacement (B1'-B5')					-1646	-1646		-1646	-1646
Second Life Transportation (A4')					2629	2629		2629	2629
Second Life Primary Production (A1'-A3')								27200	27200
First Life External Impacts (D) *A5 not included									
First Life End of Life (C1-C4) *A5 not included		4167	3605		3969	3969		4167	4167
First Life Maintenance and replacement (B1-B5) *A5 not included		-3292	-3292		-1646	-1646		-1646	-1646
First Life Transportation (A4) *A5 not included		2629	2629		2629	2629		2629	2629
First Life Primary Production (A1-A3)		27200	27200		27200	27200		27200	27200

Figure 55: Concrete with recycled concrete and SCMs (including the carbonation during lifetime)



	120_I	120_RC	120_L	60_RU_I	60_RU_RC	60_RU_L	60_RC_I	60_RC_RC	60_RC_L
Second Life External Impacts (D') *can't take this into account				-107698	0	-20627	-107698	0	-20627
Second Life End of Life (C1'-C4')				220611	216132	243559	220611	216132	243559
Second Life Maintenance and replacement (B1'-B5')				0	0	0	0	0	0
Second Life Transportation (A4')				1098	1098	1098	1098	1098	1098
Second Life Primary Production (A1'-A3')							-175785	-175785	-175785
First Life External Impacts (D) *A5 not included	-107698	-2193	-20627				-2193	-2193	-2193
First Life End of Life (C1-C4) *A5 not included	220611	216132	243559	2819	2819	2819	216132	216132	216132
First Life Maintenance and replacement (B1-B5) *A5 not included	0	0	0	0	0	0	0	0	0
First Life Transportation (A4) *A5 not included	1098	1098	1098	1098	1098	1098	1098	1098	1098
First Life Primary Production (A1-A3)	-175785	-175785	-175785	-175785	-175785	-175785	-175785	-175785	-175785

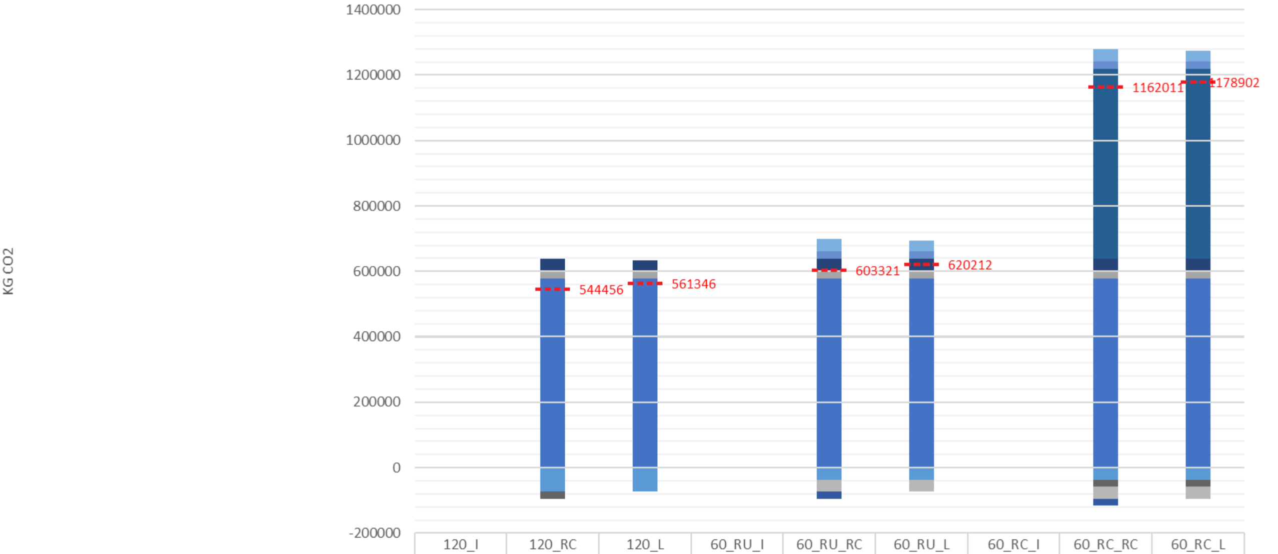
Figure 56: Wood (including the biogenic carbon)



	120_I	120_RC	120_L	60_RU_I	60_RU_RC	60_RU_L	60_RC_I	60_RC_RC	60_RC_L
Second Life External Impacts (D') *can't take this into account									
Second Life End of Life (C1'-C4')					2474			2474	
Second Life Maintenance and replacement (B1'-B5')									
Second Life Transportation (A4')					1092			1092	
Second Life Primary Production (A1'-A3')								59100	
First Life External Impacts (D) *A5 not included									
First Life End of Life (C1-C4) *A5 not included		2474			3589			2474	
First Life Maintenance and replacement (B1-B5) *A5 not included									
First Life Transportation (A4) *A5 not included		1092			1092			1092	
First Life Primary Production (A1-A3)		59100			59100			59100	

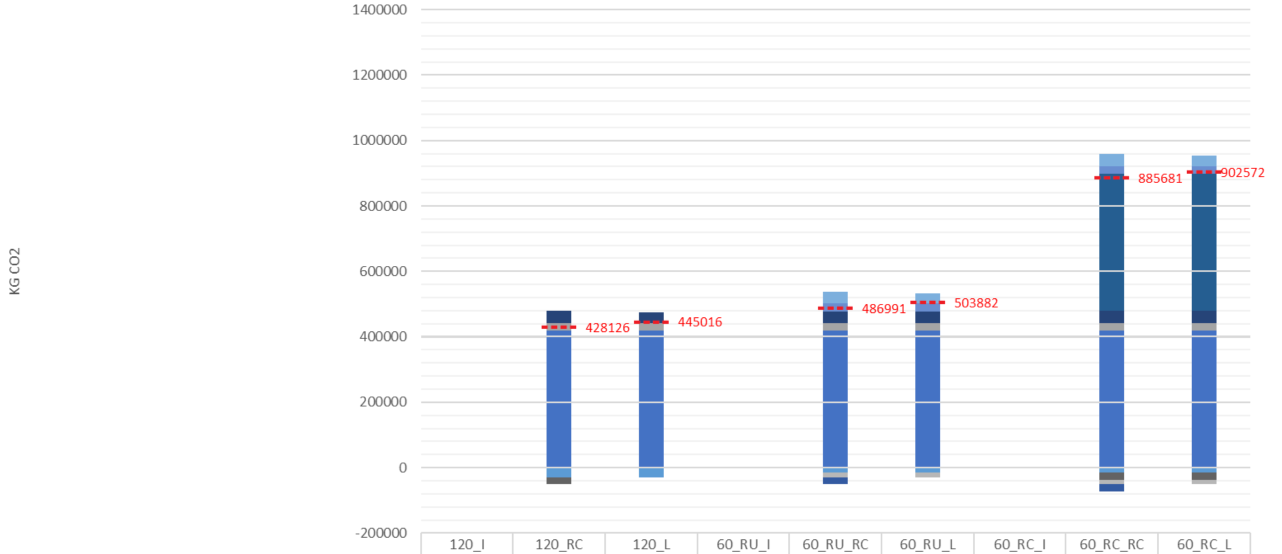
Figure 57: Steel

12.3.2 Material options and their scenarios for beams



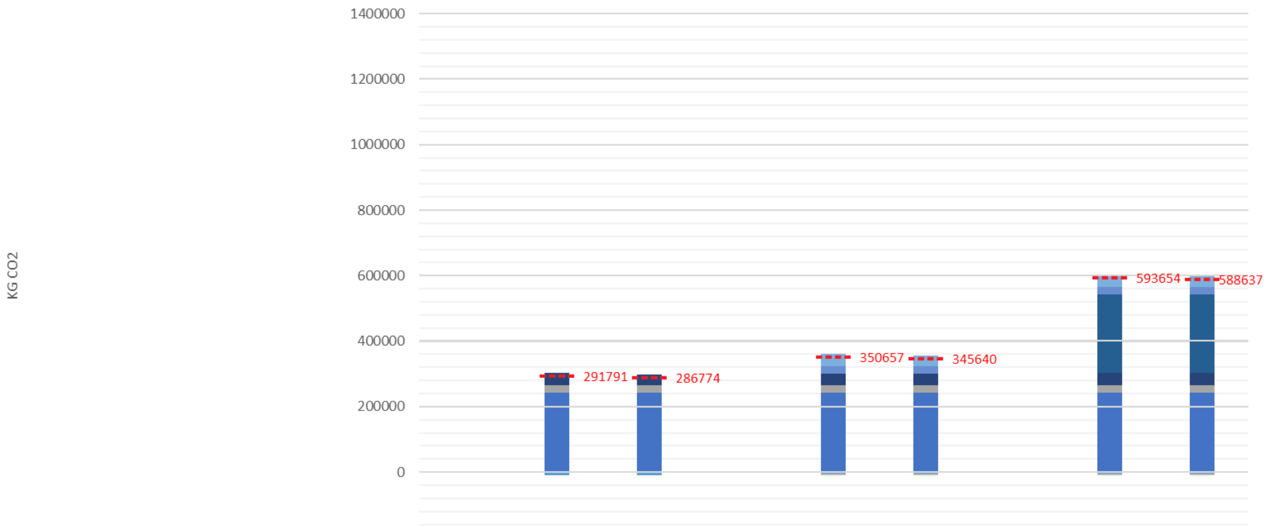
	120_I	120_RC	120_L	60_RU_I	60_RU_RC	60_RU_L	60_RC_I	60_RC_RC	60_RC_L
Second Life External Impacts (D') *can't take this into account					-21907			-21907	
Second Life End of Life (C1'-C4')					37189	32172		37189	32172
Second Life Maintenance and replacement (B1'-B5')					-36550	-36550		-36550	-36550
Second Life Transportation (A4')					23444	23444		23444	23444
Second Life Primary Production (A1'-A3')								578830	578830
First Life External Impacts (D) *A5 not included		-21907						-21907	-21907
First Life End of Life (C1-C4) *A5 not included		37189	32172		35422	35422		37189	37189
First Life Maintenance and replacement (B1-B5) *A5 not included		-73100	-73100		-36550	-36550		-36550	-36550
First Life Transportation (A4) *A5 not included		23444	23444		23444	23444		23444	23444
First Life Primary Production (A1-A3)		578830	578830		578830	578830		578830	578830

Figure 58: Standard Concrete (including the carbonation during lifetime)



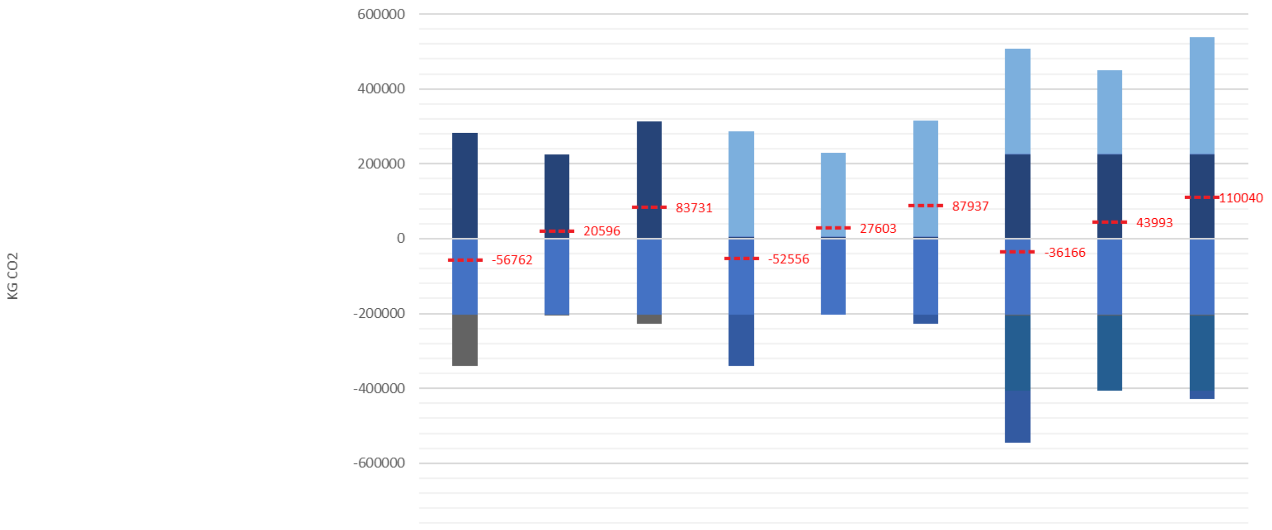
	120_I	120_RC	120_L	60_RU_I	60_RU_RC	60_RU_L	60_RC_I	60_RC_RC	60_RC_L
Second Life External Impacts (D') *can't take this into account					-21907			-21907	
Second Life End of Life (C1'-C4')					37189	32172		37189	32172
Second Life Maintenance and replacement (B1'-B5')					-14715	-14715		-14715	-14715
Second Life Transportation (A4')					23444	23444		23444	23444
Second Life Primary Production (A1'-A3')								418830	418830
First Life External Impacts (D) *A5 not included		-21907						-21907	-21907
First Life End of Life (C1-C4) *A5 not included		37189	32172		35422	35422		37189	37189
First Life Maintenance and replacement (B1-B5) *A5 not included		-29430	-29430		-14715	-14715		-14715	-14715
First Life Transportation (A4) *A5 not included		23444	23444		23444	23444		23444	23444
First Life Primary Production (A1-A3)		418830	418830		418830	418830		418830	418830

Figure 59: Concrete with SCMs (including the carbonation during lifetime)



	120_I	120_RC	120_L	60_RU_I	60_RU_RC	60_RU_L	60_RC_I	60_RC_RC	60_RC_L
Second Life External Impacts (D') *can't take this into account									
Second Life End of Life (C1'-C4')					37189	32172		37189	32172
Second Life Maintenance and replacement (B1'-B5')					-5036	-5036		-5036	-5036
Second Life Transportation (A4')					23444	23444		23444	23444
Second Life Primary Production (A1'-A3')								241230	241230
First Life External Impacts (D) *A5 not included									
First Life End of Life (C1-C4) *A5 not included		37189	32172		35422	35422		37189	37189
First Life Maintenance and replacement (B1-B5) *A5 not included		-10072	-10072		-5036	-5036		-5036	-5036
First Life Transportation (A4) *A5 not included		23444	23444		23444	23444		23444	23444
First Life Primary Production (A1-A3)		241230	241230		241230	241230		241230	241230

Figure 60: Concrete with recycled concrete and SCMs (including the carbonation during lifetime)



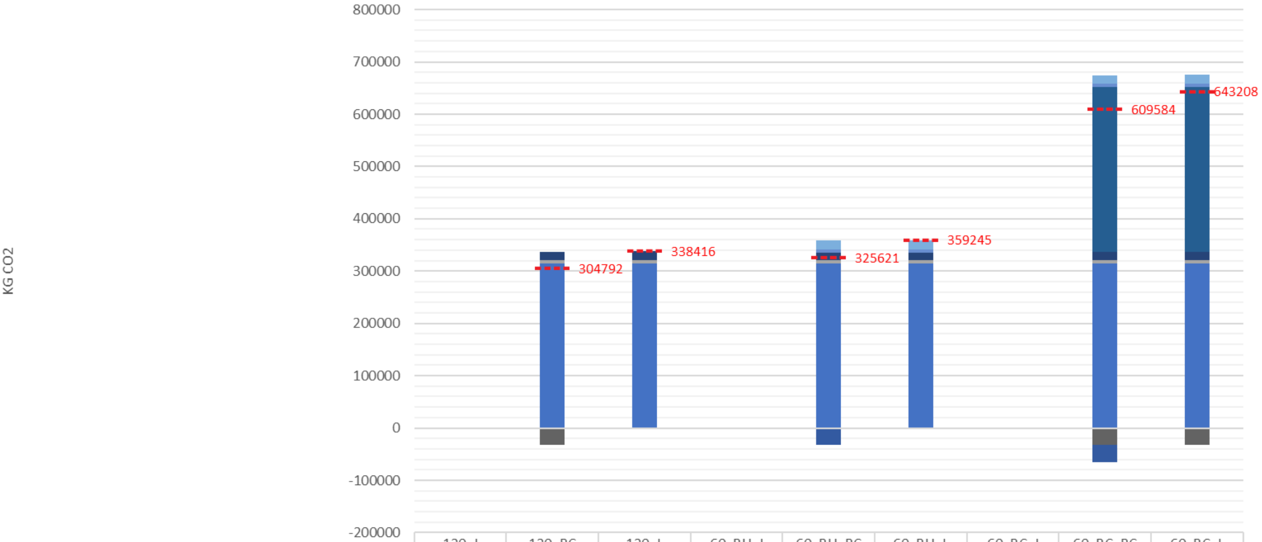
	120_I	120_RC	120_L	60_RU_I	60_RU_RC	60_RU_L	60_RC_I	60_RC_RC	60_RC_L
Second Life External Impacts (D') *can't take this into account				-137529	0	-26340	-137529	0	-20627
Second Life End of Life (C1'-C4')				281718	224348	311022	281718	224348	311022
Second Life Maintenance and replacement (B1'-B5')				0	0	0	0	0	0
Second Life Transportation (A4')				1180	1180	1180	1180	1180	1180
Second Life Primary Production (A1'-A3')							-202131	-202131	-202131
First Life External Impacts (D) *A5 not included	-137529	-2801	-26340				-2801	-2801	-2801
First Life End of Life (C1-C4) *A5 not included	281718	224348	311022	3026	3026	3026	224348	224348	224348
First Life Maintenance and replacement (B1-B5) *A5 not included	0	0	0	0	0	0	0	0	0
First Life Transportation (A4) *A5 not included	1180	1180	1180	1180	1180	1180	1180	1180	1180
First Life Primary Production (A1-A3)	-202131	-202131	-202131	-202131	-202131	-202131	-202131	-202131	-202131

Figure 61: Wood (including the biogenic carbon)

	120_I	120_RC	120_L	60_RU_I	60_RU_RC	60_RU_L	60_RC_I	60_RC_RC	60_RC_L
Second Life External Impacts (D') *can't take this into account									
Second Life End of Life (C1'-C4')					14003			14003	
Second Life Maintenance and replacement (B1'-B5')									
Second Life Transportation (A4')					6182			6182	
Second Life Primary Production (A1'-A3')								334000	
First Life External Impacts (D) *A5 not included									
First Life End of Life (C1-C4) *A5 not included		14003			20319			14003	
First Life Maintenance and replacement (B1-B5) *A5 not included									
First Life Transportation (A4) *A5 not included		6182			6182			6182	
First Life Primary Production (A1-A3)		334000			334000			334000	

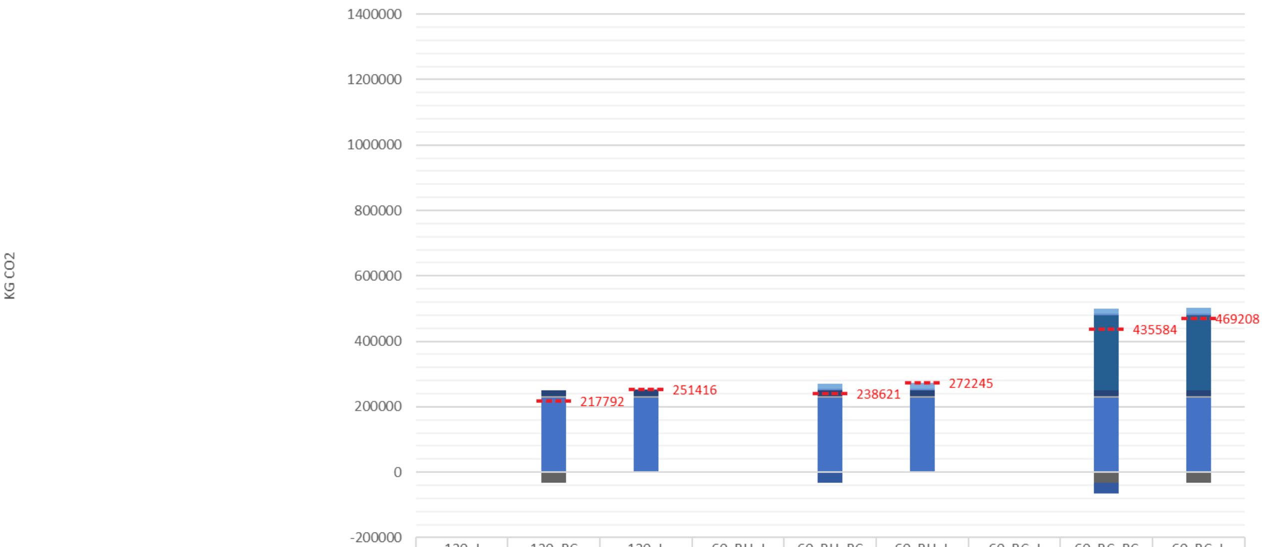
Figure 62: Steel

12.3.3 Material options and their scenarios for slabs



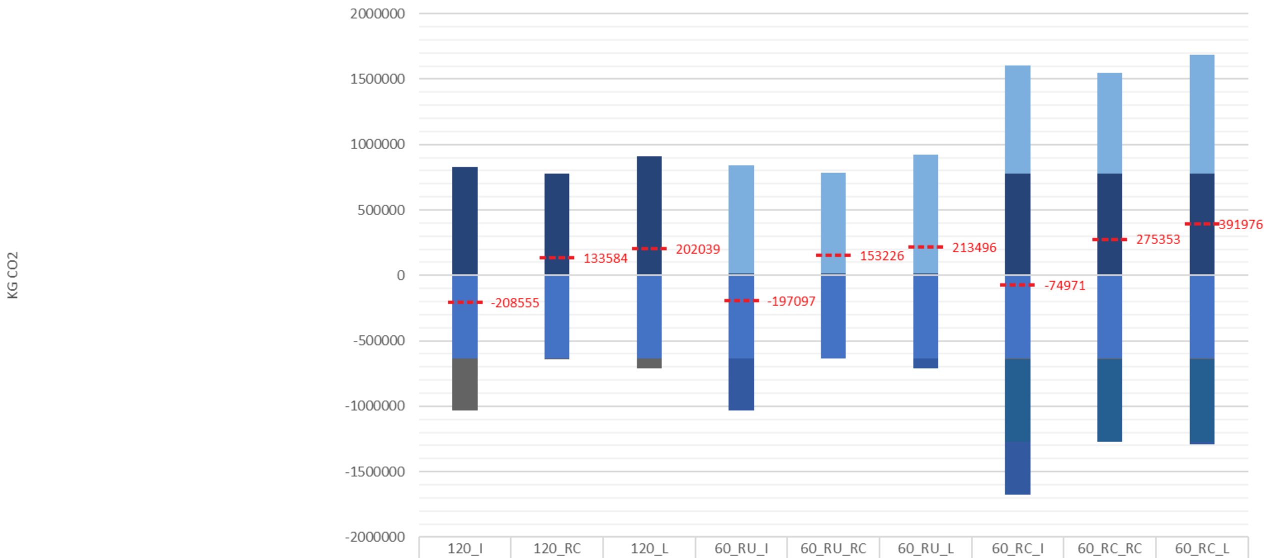
	120_I	120_RC	120_L	60_RU_I	60_RU_RC	60_RU_L	60_RC_I	60_RC_RC	60_RC_L
Second Life External Impacts (D') *can't take this into account					-32570			-32570	
Second Life End of Life (C1'-C4')					17142	18196		17142	18196
Second Life Maintenance and replacement (B1'-B5')					0	0		0	0
Second Life Transportation (A4')					5220	5220		5220	5220
Second Life Primary Production (A1'-A3')								315000	315000
First Life External Impacts (D) *A5 not included		-32570						-32570	-32570
First Life End of Life (C1-C4) *A5 not included		17142	18196		15609	15609		17142	17142
First Life Maintenance and replacement (B1-B5) *A5 not included									
First Life Transportation (A4) *A5 not included		5220	5220		5220	5220		5220	5220
First Life Primary Production (A1-A3)		315000	315000		315000	315000		315000	315000

Figure 63: Standard Concrete (including the carbonation during lifetime)



	120_I	120_RC	120_L	60_RU_I	60_RU_RC	60_RU_L	60_RC_I	60_RC_RC	60_RC_L
Second Life External Impacts (D') *can't take this into account					-32570			-32570	
Second Life End of Life (C1'-C4')					17142	18196		17142	18196
Second Life Maintenance and replacement (B1'-B5')									
Second Life Transportation (A4')					5220	5220		5220	5220
Second Life Primary Production (A1'-A3')								228000	228000
First Life External Impacts (D) *A5 not included		-32570						-32570	-32570
First Life End of Life (C1-C4) *A5 not included		17142	18196		15609	15609		17142	17142
First Life Maintenance and replacement (B1-B5) *A5 not included									
First Life Transportation (A4) *A5 not included		5220	5220		5220	5220		5220	5220
First Life Primary Production (A1-A3)		228000	228000		228000	228000		228000	228000

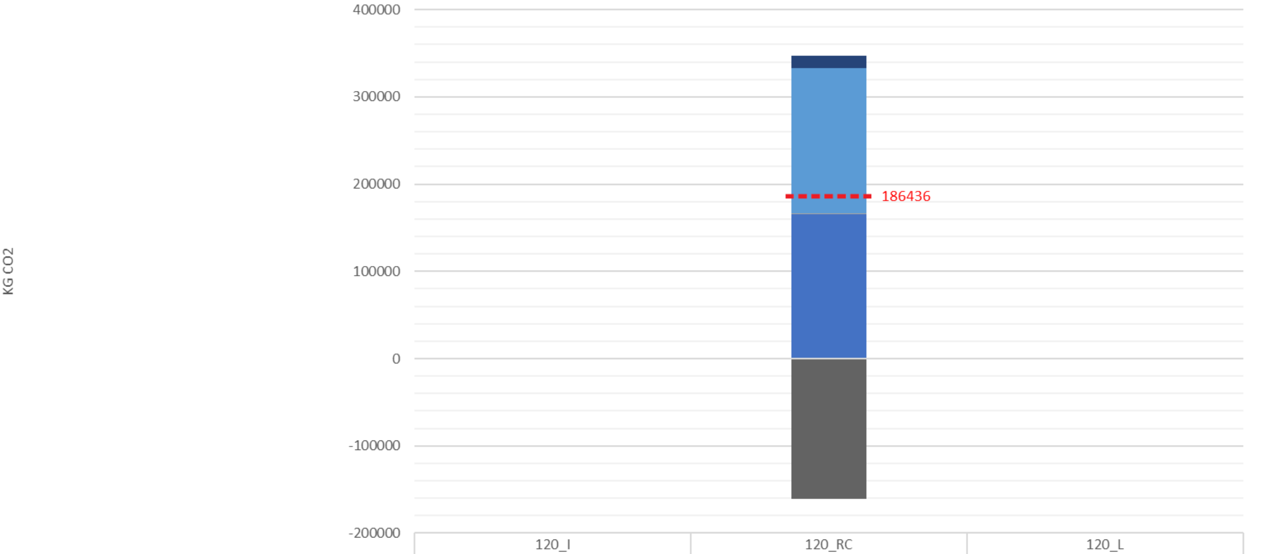
Figure 64: Concrete with SCMs (including the carbonation during lifetime)



	120_I	120_RC	120_L	60_RU_I	60_RU_RC	60_RU_L	60_RC_I	60_RC_RC	60_RC_L
Second Life External Impacts (D') *can't take this into account				-401932	0	-76980	-401932	0	-20627
Second Life End of Life (C1'-C4')				823327	771719	908969	823327	771719	908969
Second Life Maintenance and replacement (B1'-B5')				0	0	0	0	0	0
Second Life Transportation (A4')				2710	2710	2710	2710	2710	2710
Second Life Primary Production (A1'-A3')							-632660	-632660	-632660
First Life External Impacts (D) *A5 not included	-401932	-8185	-76980				-8185	-8185	-8185
First Life End of Life (C1-C4) *A5 not included	823327	771719	908969	8748	8748	8748	771719	771719	771719
First Life Maintenance and replacement (B1-B5) *A5 not included	0	0	0	0	0	0	0	0	0
First Life Transportation (A4) *A5 not included	2710	2710	2710	2710	2710	2710	2710	2710	2710
First Life Primary Production (A1-A3)	-632660	-632660	-632660	-632660	-632660	-632660	-632660	-632660	-632660

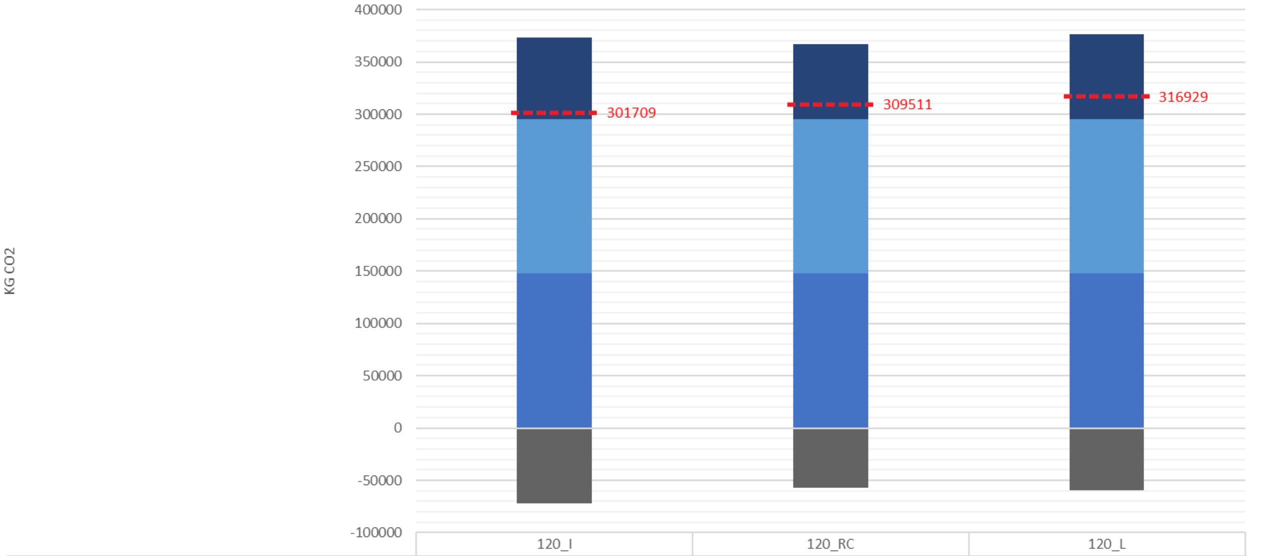
Figure 65: Wood (including the biogenic carbon)

12.3.4 Material options and their scenarios for façade



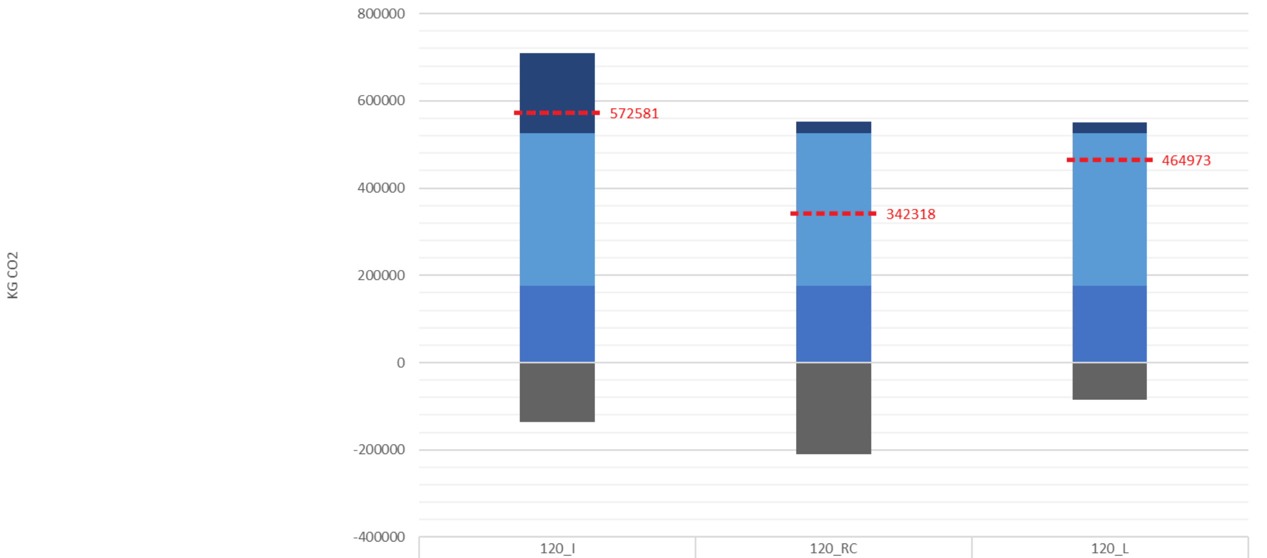
	120_I	120_RC	120_L
Second Life External Impacts (D') *can't take this into account			
Second Life End of Life (C1'-C4')			
Second Life Maintenance and replacement (B1'-B5')			
Second Life Transportation (A4')			
Second Life Primary Production (A1'-A3')			
First Life External Impacts (D) *A5 not included		-160516	
First Life End of Life (C1-C4) *A5 not included		14430	
First Life Maintenance and replacement (B1-B5) *A5 not included		165756	
First Life Transportation (A4) *A5 not included		1010	
First Life Primary Production (A1-A3)		165756	

Figure 66: Aluminium frames



	120_I	120_RC	120_L
Second Life External Impacts (D') *can't take this into account			
Second Life End of Life (C1'-C4')			
Second Life Maintenance and replacement (B1'-B5')			
Second Life Transportation (A4')			
Second Life Primary Production (A1'-A3')			
First Life External Impacts (D) *A5 not included	-71793	-57228	-59773
First Life End of Life (C1-C4) *A5 not included	78085	71322	81285
First Life Maintenance and replacement (B1-B5) *A5 not included	147598	147598	147598
First Life Transportation (A4) *A5 not included	220	220	220
First Life Primary Production (A1-A3)	147598	147598	147598

Figure 67: Wood-Aluminium frames (including the biogenic carbon)



	120_I	120_RC	120_L
Second Life External Impacts (D') *can't take this into account			
Second Life End of Life (C1'-C4')			
Second Life Maintenance and replacement (B1'-B5')			
Second Life Transportation (A4')			
Second Life Primary Production (A1'-A3')			
First Life External Impacts (D) *A5 not included	-136839	-210032	-85468
First Life End of Life (C1-C4) *A5 not included	183210	26140	24231
First Life Maintenance and replacement (B1-B5) *A5 not included	350000	350000	350000
First Life Transportation (A4) *A5 not included	1210	1210	1210
First Life Primary Production (A1-A3)	175000	175000	175000

Figure 68: PVC U frames

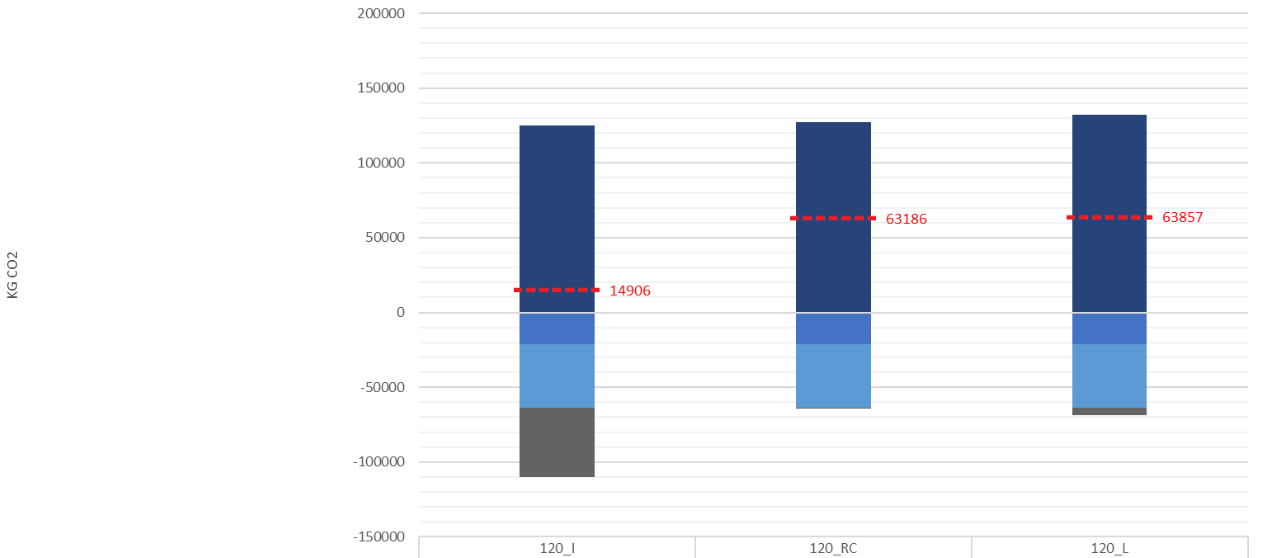
12.3.5 Material options and their scenarios for façade awnings

	120_RC	60_RU_RC	60_RC_RC
Second Life External Impacts (D') *can't take this into account			
Second Life End of Life (C1'-C4')		207	207
Second Life Maintenance and replacement (B1'-B5')			
Second Life Transportation (A4')		252	252
Second Life Primary Production (A1'-A3')			80287
First Life External Impacts (D) *A5 not included			
First Life End of Life (C1-C4) *A5 not included	207	207	207
First Life Maintenance and replacement (B1-B5) *A5 not included			
First Life Transportation (A4) *A5 not included	252	252	252
First Life Primary Production (A1-A3)	80287	80287	80287

Figure 69: Aluminium

	120_I	120_RC	120_L
Second Life External Impacts (D') *can't take this into account			
Second Life End of Life (C1'-C4')			
Second Life Maintenance and replacement (B1'-B5')			
Second Life Transportation (A4')			
Second Life Primary Production (A1'-A3')			
First Life External Impacts (D) *A5 not included	-37107	-352	-3313
First Life End of Life (C1-C4) *A5 not included	64178	59046	62171
First Life Maintenance and replacement (B1-B5) *A5 not included	-2581	-2581	-2581
First Life Transportation (A4) *A5 not included	220	220	220
First Life Primary Production (A1-A3)	-1291	-1291	-1291

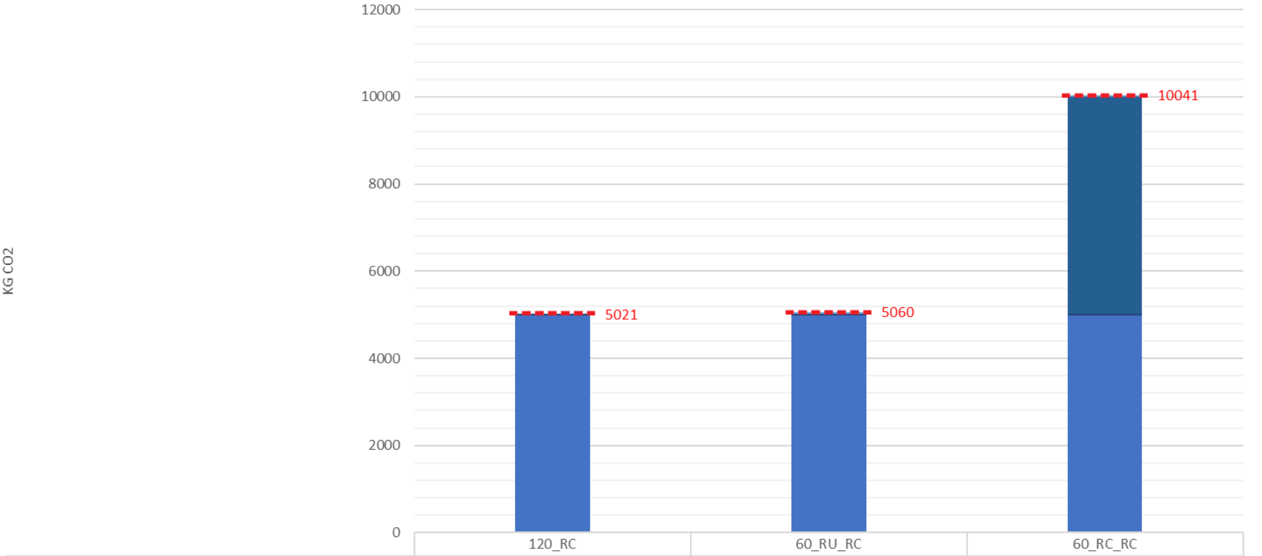
Figure 70: Wood (including the biogenic carbon)



	120_I	120_RC	120_L
Second Life External Impacts (D') *can't take this into account			
Second Life End of Life (C1'-C4')			
Second Life Maintenance and replacement (B1'-B5')			
Second Life Transportation (A4')			
Second Life Primary Production (A1'-A3')			
First Life External Impacts (D) *A5 not included	-46872	-547	-5149
First Life End of Life (C1-C4) *A5 not included	124996	126951	132225
First Life Maintenance and replacement (B1-B5) *A5 not included	-42297	-42297	-42297
First Life Transportation (A4) *A5 not included	227	227	227
First Life Primary Production (A1-A3)	-21148	-21148	-21148

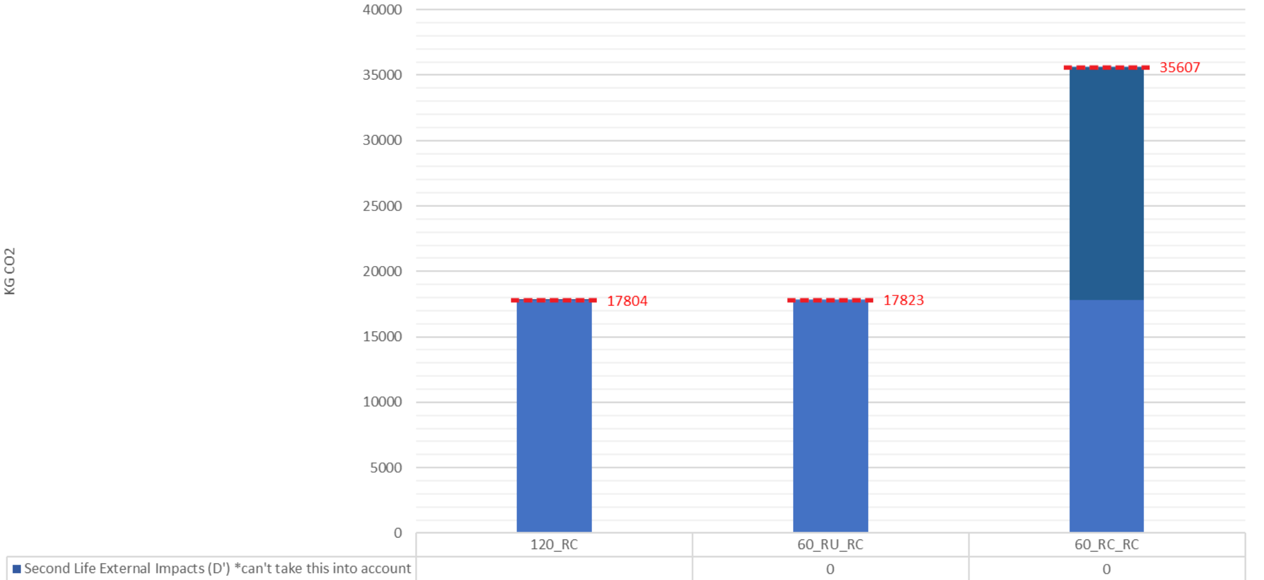
Figure 71: Bamboo (including the biogenic carbon)

12.3.6 Material options and their scenarios for insulation



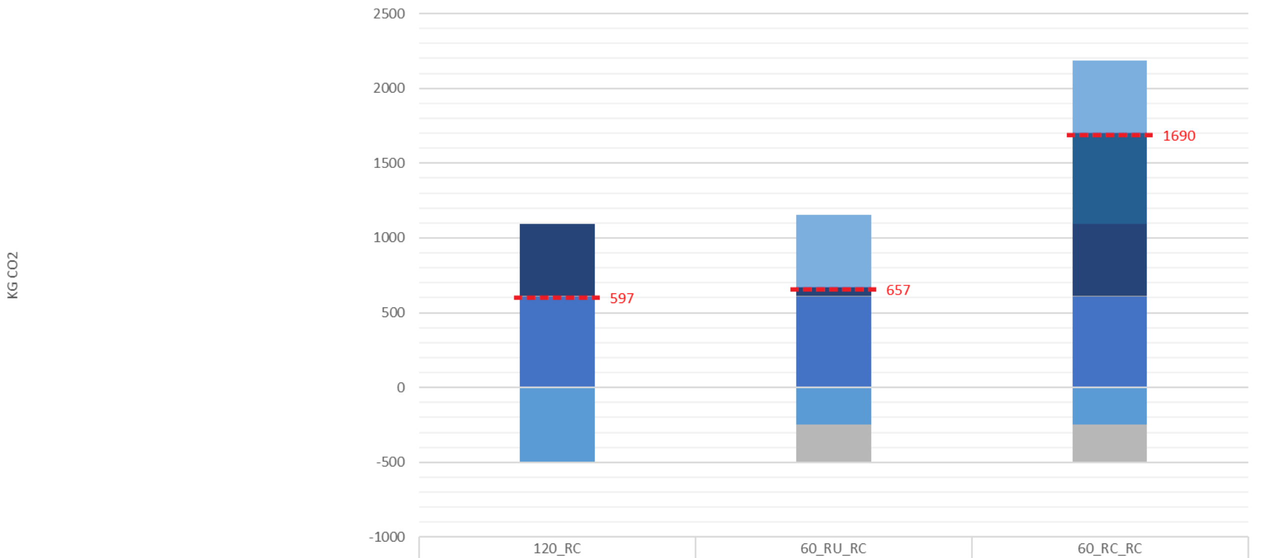
	120_RC	60_RU_RC	60_RC_RC
Second Life External Impacts (D') *can't take this into account		0	0
Second Life End of Life (C1'-C4')		34	34
Second Life Maintenance and replacement (B1'-B5')			
Second Life Transportation (A4')		5.7	5.7
Second Life Primary Production (A1'-A3')			4981
First Life External Impacts (D) *A5 not included	0	0	0
First Life End of Life (C1-C4) *A5 not included	34	34	34
First Life Maintenance and replacement (B1-B5) *A5 not included			
First Life Transportation (A4) *A5 not included	5.7	5.7	5.7
First Life Primary Production (A1-A3)	4981	4981	4981

Figure 72: Rockwool



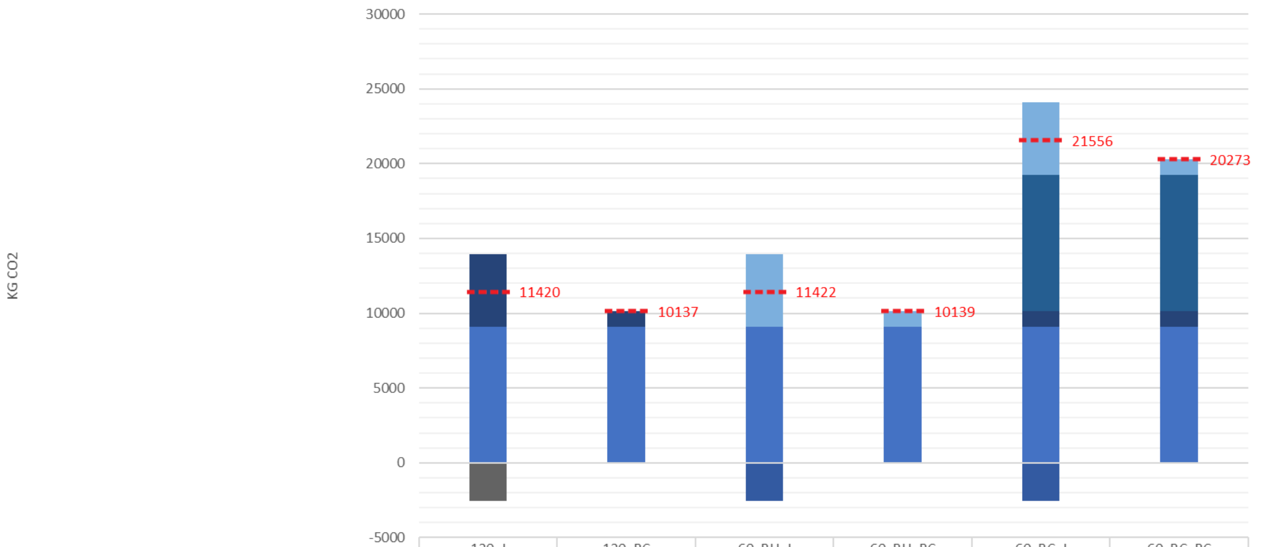
	120_RC	60_RU_RC	60_RC_RC
Second Life External Impacts (D') *can't take this into account		0	0
Second Life End of Life (C1'-C4')		6	6
Second Life Maintenance and replacement (B1'-B5')			
Second Life Transportation (A4')		13	13
Second Life Primary Production (A1'-A3')			17785
First Life External Impacts (D) *A5 not included	0	0	0
First Life End of Life (C1-C4) *A5 not included	6	6	6
First Life Maintenance and replacement (B1-B5) *A5 not included			
First Life Transportation (A4) *A5 not included	13	13	13
First Life Primary Production (A1-A3)	17785	17785	17785

Figure 73: Glass wool



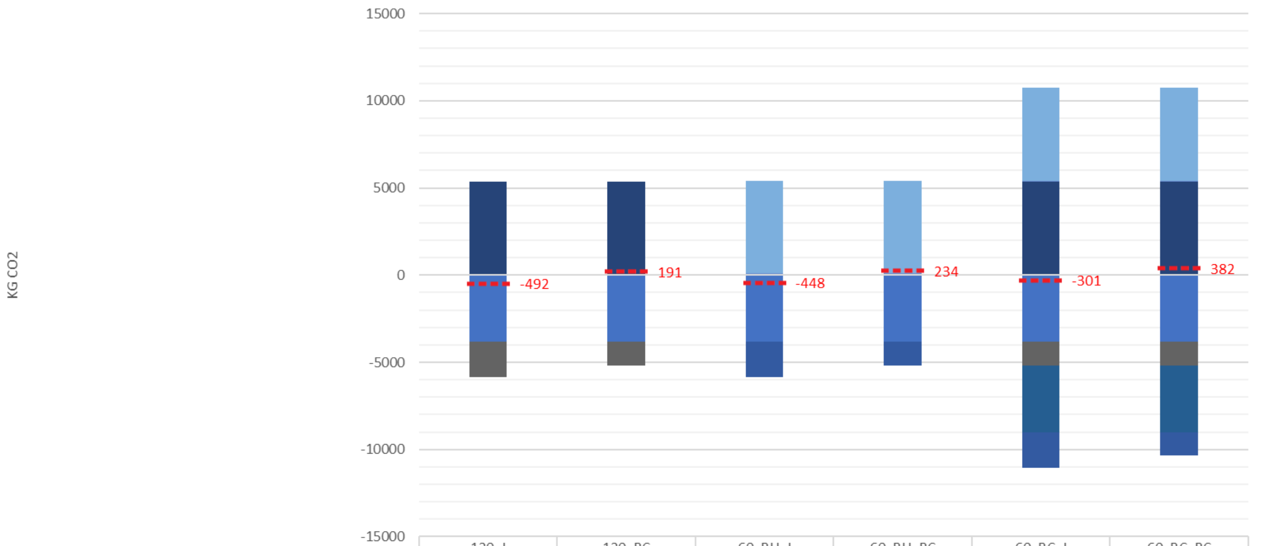
	120_RC	60_RU_RC	60_RC_RC
Second Life External Impacts (D') *can't take this into account		0	0
Second Life End of Life (C1'-C4')		479	479
Second Life Maintenance and replacement (B1'-B5')		-247	-247
Second Life Transportation (A4')		6.2	6.2
Second Life Primary Production (A1'-A3')			608
First Life External Impacts (D) *A5 not included	0	0	0
First Life End of Life (C1-C4) *A5 not included	479	53	479
First Life Maintenance and replacement (B1-B5) *A5 not included	-495	-247	-247
First Life Transportation (A4) *A5 not included	6.2	6.2	6.2
First Life Primary Production (A1-A3)	608	608	608

Figure 74: Hempcrete (including the carbonation during lifetime)



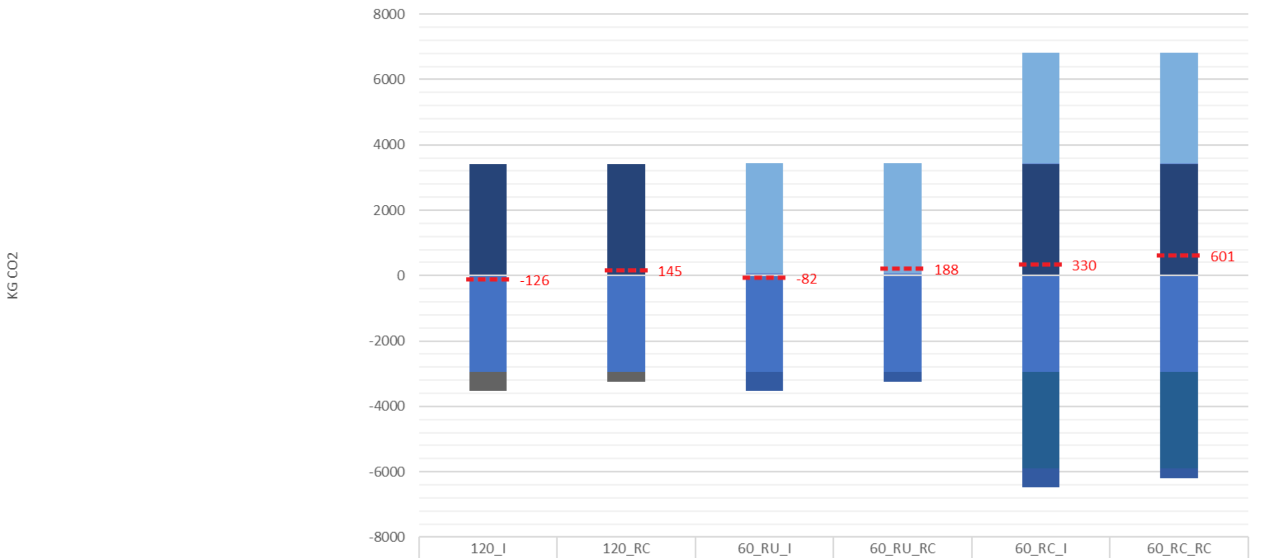
	120_I	120_RC	60_RU_I	60_RU_RC	60_RC_I	60_RC_RC
Second Life External Impacts (D') *can't take this into account			-2528	0	-2528	0
Second Life End of Life (C1'-C4')			4855	1044	4855	1044
Second Life Maintenance and replacement (B1'-B5')						
Second Life Transportation (A4')			2.7	2.7	2.7	2.7
Second Life Primary Production (A1'-A3')					9090	9090
First Life External Impacts (D) *A5 not included	-2528	0				
First Life End of Life (C1-C4) *A5 not included	4855	1044	0	0	1044	1044
First Life Maintenance and replacement (B1-B5) *A5 not included						
First Life Transportation (A4) *A5 not included	2.7	2.7	2.7	2.7	2.7	2.7
First Life Primary Production (A1-A3)	9090	9090	9090	9090	9090	9090

Figure 75: EPS foam



	120_I	120_RC	60_RU_I	60_RU_RC	60_RC_I	60_RC_RC
Second Life External Impacts (D') *can't take this into account			-2044	-1361	-2044	-1361
Second Life End of Life (C1'-C4')			5328	5328	5328	5328
Second Life Maintenance and replacement (B1'-B5')						
Second Life Transportation (A4')			43.3	43.3	43.3	43.3
Second Life Primary Production (A1'-A3')					-3819	-3819
First Life External Impacts (D) *A5 not included	-2044	-1361			-1361	-1361
First Life End of Life (C1-C4) *A5 not included	5328	5328			5328	5328
First Life Maintenance and replacement (B1-B5) *A5 not included						
First Life Transportation (A4) *A5 not included	43.3	43.3	43.3	43.3	43.3	43.3
First Life Primary Production (A1-A3)	-3819	-3819	-3819	-3819	-3819	-3819

Figure 76: Wood fibre (including the carbonation during lifetime)



	120_I	120_RC	60_RU_I	60_RU_RC	60_RC_I	60_RC_RC
Second Life External Impacts (D') *can't take this into account			-582	-312	-582	-312
Second Life End of Life (C1'-C4')			3360	3360	3360	3360
Second Life Maintenance and replacement (B1'-B5')						
Second Life Transportation (A4')			43.5	43.5	43.5	43.5
Second Life Primary Production (A1'-A3')					-2947	-2947
First Life External Impacts (D) *A5 not included	-582	-312				
First Life End of Life (C1-C4) *A5 not included	3360	3360			3360	3360
First Life Maintenance and replacement (B1-B5) *A5 not included						
First Life Transportation (A4) *A5 not included	43.5	43.5	43.5	43.5	43.5	43.5
First Life Primary Production (A1-A3)	-2947	-2947	-2947	-2947	-2947	-2947

Figure 77: Cellulose (including the carbonation during lifetime)

Towards **Zero Carbon** Buildings

Design guidelines to achieve low embodied carbon buildings

Manual for architects, engineers and project managers

Preface

The building industry accounts for almost 40% of the total carbon emissions that are directly responsible for climate change. The buildings are now deploying energy-efficient solutions to lower carbon emissions from the operational phase. This adversely affects the share of embodied carbon emissions of building materials. The graduation thesis aimed to study and compare the life cycle impact of different materials in building applications. The life cycle assessment method was adapted using certain assumptions to account for circular design approaches. End-of-life scenarios for all the materials were formed and compared using the assessment method. The analysis of materials in different building applications presented a significant difference in embodied carbon emissions.

This manual explains the step-by-step approach to integrate the carbon footprint aspect in building design. The assessment method and results from graduation thesis are used to derive guidelines for this manual. The defined approach covers the stages from project inception until material finalization. The goal to reduce embodied carbon emissions is thus achieved by careful selection of materials and recommended strategies.

Contents

Limitations

The guidelines in this manual are based on the graduation thesis- ‘Towards Zero Carbon Buildings’. Some limitations of the design guidelines are:

- The research focused only on the Global Warming Potential (GWP) indicator of the building materials, i.e. CO_2 equivalents of Greenhouse gases. It does not consider other impact indicators such as acidification, eutrophication potential etc.

- There are limited number of materials studied in the research representing broad material families. These guidelines are based on the findings from the research and thus, do not show results of materials beyond the scope.

- Alternate materials proposed in the guidelines have equivalent structural properties. However, other properties such as thermal or acoustic are not considered, but attempted to be similar.

- The demonstrated end of life scenarios are assumed to have 100% conditions of incineration/ reuse/ recycle/ landfill. However, due to limited technology, the current practical conditions do not allow that. Therefore, the guidelines must be used as target goals while designing.

- The guidelines are broadly defined for a typical construction. There may be more conditions in this flowchart of design that are not acknowledged. Closest resembling solutions in the defined steps can still be followed to achieve estimated results.

- The use of alternate materials may cause a consequential need for other solutions, such as fireproof coating or heavier scaffolding. Therefore, reassessment of design while detailing could lead to more accurate results.

The material data used in the research are extracted from third-party verified EPDs and other published literature.

Overview

0 Building definition

- Type of building
- Structurally and economically feasible materials
- Other building components and material quantities

1 Determining material family

Based on research, determining lowest carbon footprint material family

2 Determining material and service life of component

Choosing lowest carbon footprint materials based on specific parameters, and determining the appropriate service life of component based on building life

3 Defining the end of life

Using the results from defined scenarios, defining an appropriate EOL

Building Definition

0

The type of construction has a huge influence on the embodied carbon emissions of the project. A clear definition of building is important to assess its carbon emissions and compare it with other benchmark projects.

The definition of building includes:

- Type of construction
  - New construction/ Renovation
  - Educational/ Commercial/ Residential/ Office/ Other
  - High-rise/ Mid-rise/ Small scale construction
- Built-up Area
- Anticipated Life Span

In this section, the importance of building life span and construction type is explained along with other necessary steps for assessment.

Important recommendations:

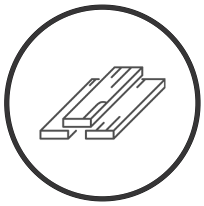
- Adaptive reuse of a construction must be preferred if possible. Existing buildings are a representation of existing carbon emissions in the atmosphere.
- Low/Mid-rise construction must be preferred if possible. This allows design for disassembly and light-weight timber construction.
- The type of construction must not dictate the design completely to allow adaptive reuse in future.

a. Anticipated life span

The life span of a construction plays an important role in defining the carbon emissions over its life. Besides an impact on the operational emissions, it impacts the embodied emissions too. The replacement and maintenance of building materials contribute considerably towards the total emissions.

The substructure and superstructure of a building contributes to an average of 60% embodied carbon emissions. Therefore, the life span of a construction must be designed as long as possible with adaptive design strategies for flexible use in future.

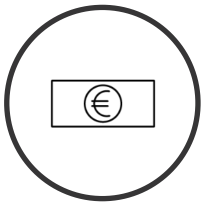
From the research, timber structure may have a life span of more than 120 years and results in the lowest embodied carbon emissions. A construction using similar materials, but with shorter life span may also have lower carbon emissions if designed with circular strategies.



b. Economic and structural feasibility

The concept building design must be studied with different building materials to understand structural and economic feasibility of construction.

An estimate of quantity of building materials is useful to further assess the carbon footprint.

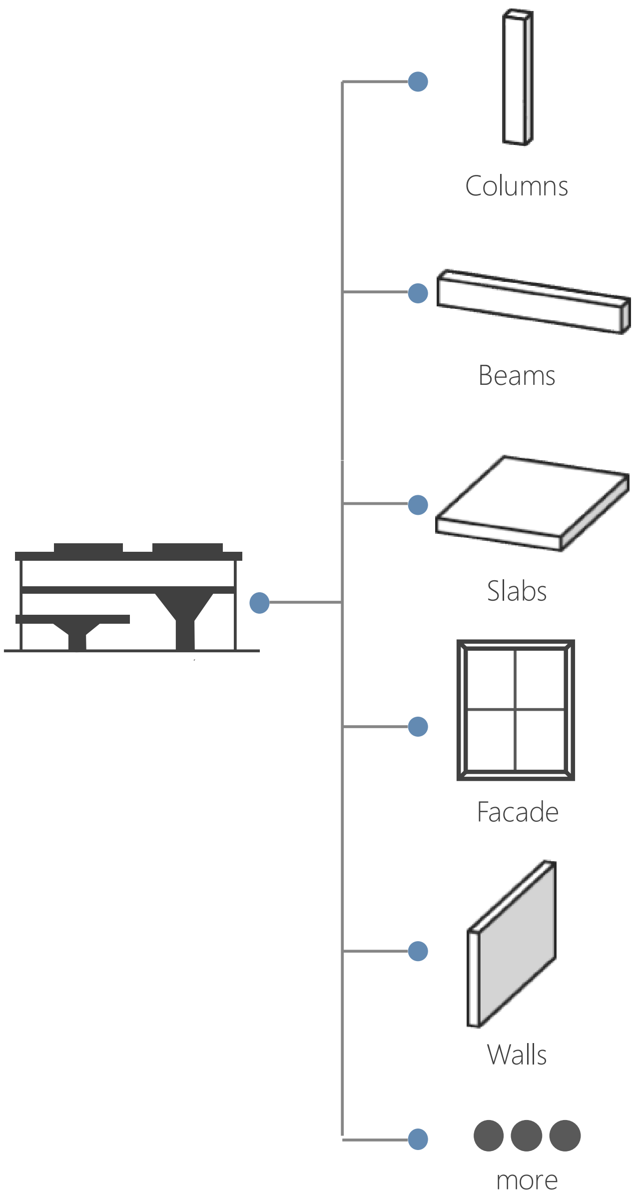


Important recommendations:

- The role of structural consultant at an early design stage is important for the feasibility study of different structural materials.

c. Determining other building components and quantities

The building must be further divided into separate components for assessment along with the estimated quantities.



Important recommendations:

- Use of some BIM or other tools (carbon designer in One Click LCA) allows estimation of material quantities for concept building design.

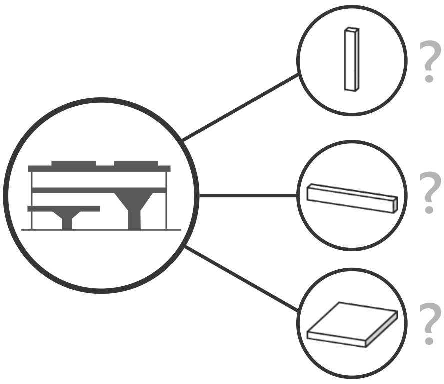
1

Determining material family

The structural and economic feasibility study of the building may result in material options other than all-wood construction. This may be due to structurally unfeasible wood columns in high-rise construction or its economic unfeasibility in some countries.

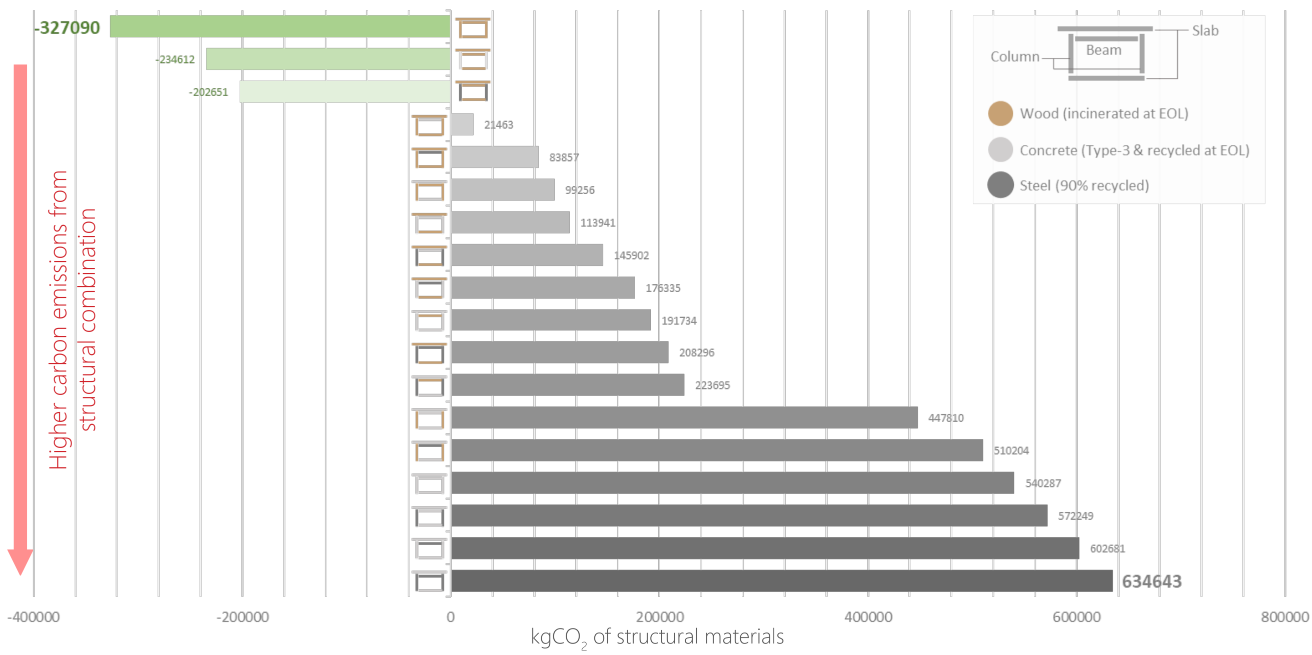
In such cases, the structure of the building may be reiterated with other combinations of columns, beams and slabs to lower the carbon footprint. The results from research may be used as basic guidance tool to choose the feasible option with lowest carbon emissions.

In the bar chart shown below, the icons next to each bar depict the combination of material type used in each structural element- column, beam and slab. The carbon emissions reduce as we go down in the bar chart.

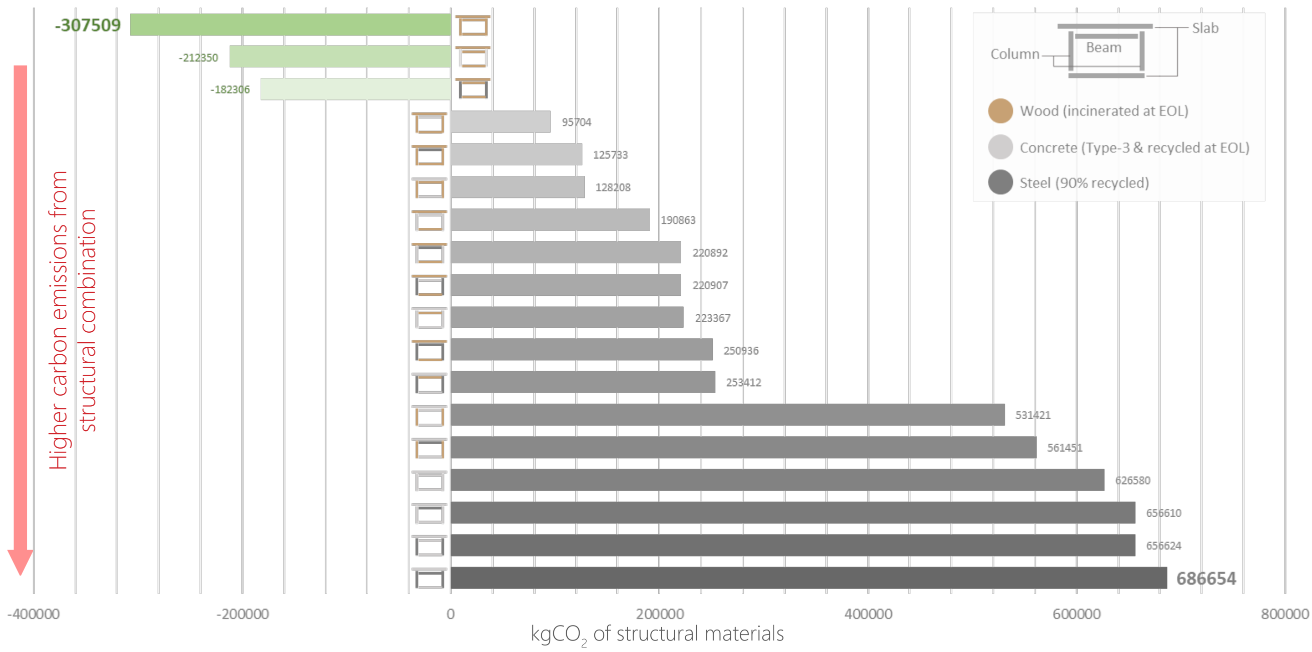


Important recommendations:

- Based on results, using wooden slabs have higher impact in reducing the total carbon emissions than its use in beams or columns.



Combinations for structure with anticipated life span of 120 years.



Combinations for structure with anticipated life span of 60 years.

2

Determining material and service life of building component

To determine a suitable material and its service life, some parameters must be checked from the declarations such as EPD by manufacturers. These are mentioned below in order of their importance:

- $GWP_{A1\text{-}A3}$: declared carbon footprint (A1-A3) (kgCO_2eq./ est. material quantity)
- Service life
- Energy recovery potential (if any upon incineration at EOL) (in kgCO_2eq./ est. material quantity)
- Local availability
- Biogenic carbon stored (if any) (kgCO_2eq./ est. material quantity)

a. Parameters influencing the environmental impact of materials

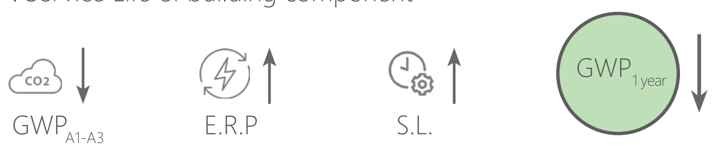
The environmental impact of materials is most influenced by the GWP_{A1-A3}, service life and energy recovery potential. It cannot be interpret individually by any one parameter. The rest of the life cycle stages (maintenance, demolition etc) are insignificant as compared to the GWP_{A1-A3} and are also similar for different materials in most cases. Energy recovery potential (E.R.P) from incineration is estimated to be between 200-500 $kgCO_2eq./m^3$ of material.

Therefore, a basic formula to compare the impact of materials is derived as:

$$GWP_{1\,year} = \frac{GWP_{A1-A3} - E.R.P.}{S.L.}$$

where

$GWP_{1\,year}$: Global warming potential (GWP) per 1 year of service life
GWP_{A1-A3} : Total carbon footprint ($kgCO_2eq.$/ est. material quantity)
E.R.P. : Energy recovery potential (if any) ($kgCO_2eq.$/ est. material quantity)
S.L. : Service Life of building component



The other parameters (local availability and biogenic carbon stored) are also important while determining the material, but does not have a lot of influence on the results. Materials with the closest proximity to the building site must be preferred to lower the transportation carbon emissions. The bio-based materials with highest biogenic carbon stored must also be preferred to increase the carbon stored in technosphere.

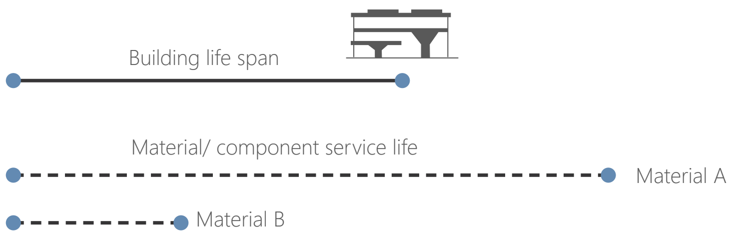
The materials with lowest $GWP_{1\,year}$ value in each building application shall provide the suitable material option.

Important recommendations:

- Materials/ building components with highest service must usually be preferred to allow circular use even after building life span
- Bamboo has a higher carbon sequestration potential than wood

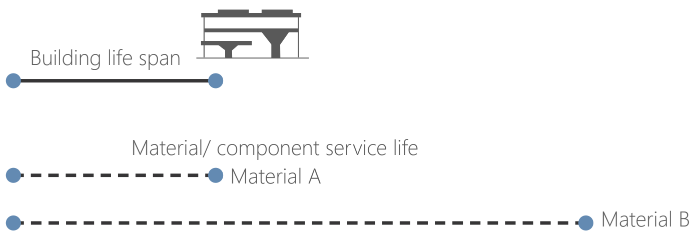
b. Determining the service life of materials/ building components

The service life of materials are declared by the manufacturers and must always be taken into consideration while choosing materials. The choice of suitable material life is explained with an example below:



- The materials with service life equal to or greater than the building life span (Material A) are commonly the preferred choice. This choice is justified if the $GWP_{1\ year}$ of material A is lesser than material B.

- However, if $GWP_{1\ year}$ of material B is considerably lesser than material A, material B must be preferred to achieve lower environmental impact. This may result in higher price. Therefore, a considerate approach is needed.



The materials used in building application must always be compared with other possible materials having longer service life and lower $GWP_{1\ year}$. This allows a circular use of materials even after building life.

3

Defining the end-of-life

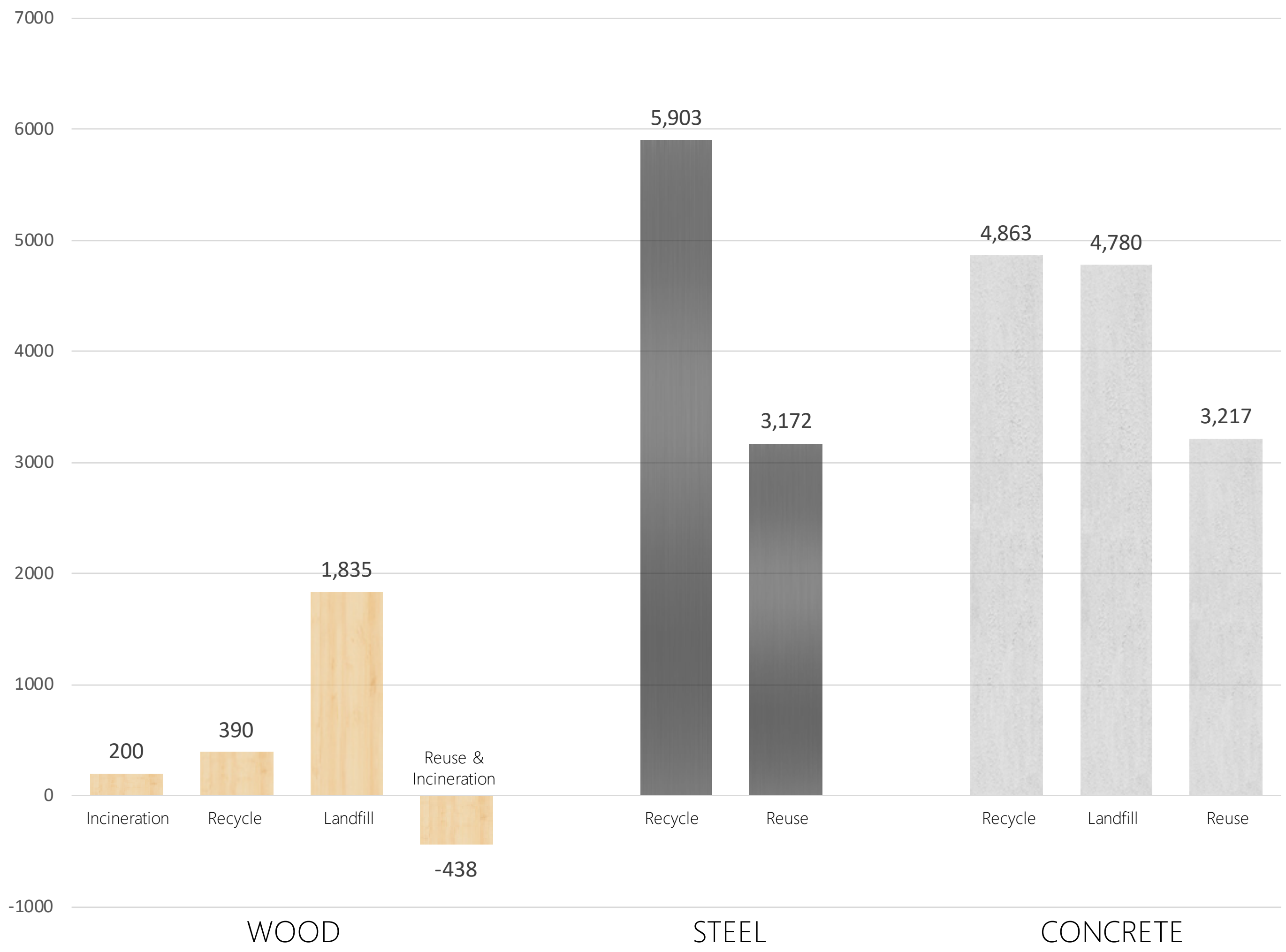
The research to assess several end-of-life scenarios for materials was conducted for each building component. While the impact varied between the building components, the trend of best and worst end-of-life scenarios remained similar due to the assumptions.

An example of results for beam is shown comparing the $GWP_{1\ year}$ values of wood, steel and concrete including the end-of-life carbon emissions. The results are simplified to show the comparison of carbon footprint per year by assuming

- the service life of all the materials are 120 years
- the end-of-life for incineration/ recycle/ landfill occurs at 60 years
- the reuse scenario shows the materials being used until end of service life
- concrete with the lowest carbon footprint from research is shown

Important recommendations:

- The design strategies must be governed by the anticipated end-of-life for the building materials
- Module D/ benefits from end-of-life must be carefully accounted (only once), to understand the holistic picture of life cycle impacts



The results from above illustration must be interpret as:

- Bio-based material incineration and reuse

Incineration scenarios of wood, bamboo, wood fiber insulation, etc has the lowest carbon emissions. However, the use of such materials for longer period results in even lower carbon footprint as shown in 'reuse & incineration'.

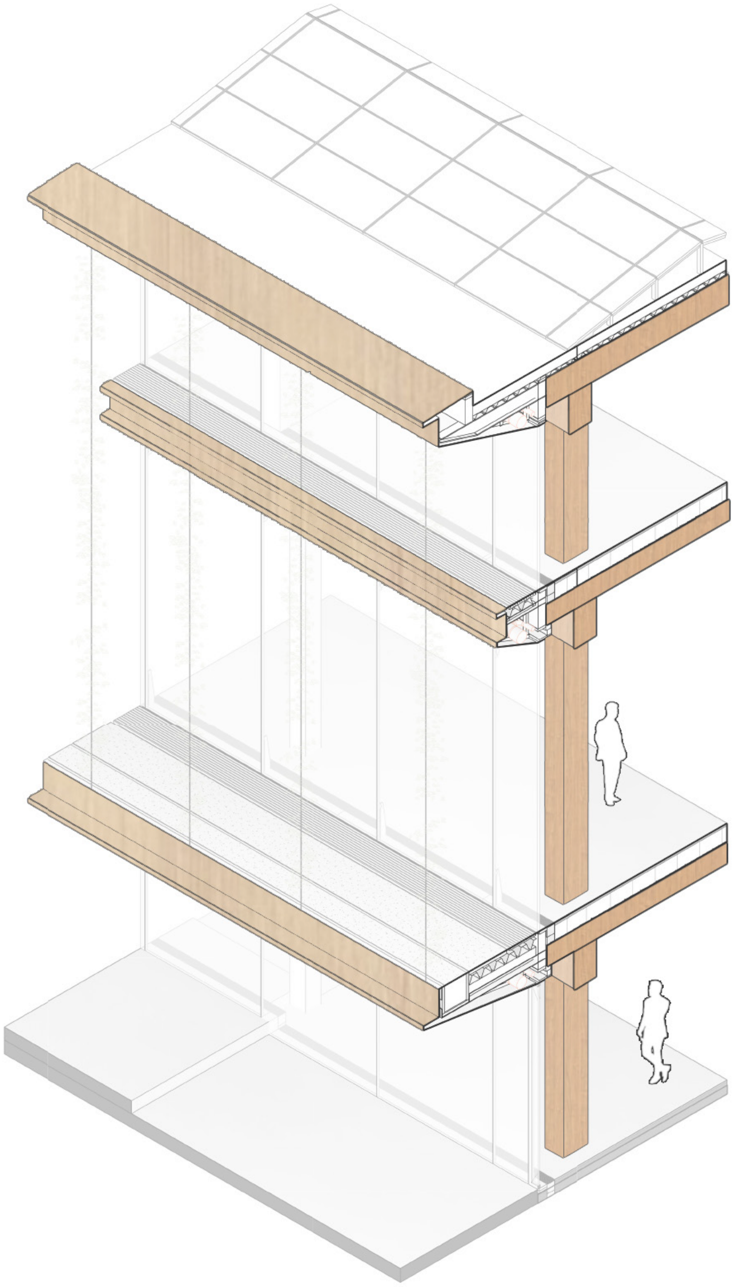
- Reuse and Recycle

In all the materials, reuse scenario results in almost half the carbon emissions as of recycle. This is due to energy intensive recycling processes that has higher carbon equivalent as compared to negligible carbon emissions involved in reuse.

- Landfill

Landfill of wood presents higher carbon emissions due to release of carbon dioxide in soil. It is also an energy intensive process with almost no energy recovery and therefore, must not be practiced. Landfill of other materials such as concrete, PVC, etc may also be harmful for the environment.

Summary



~120% lower
embodied carbon emissions

An estimated result from assessment of a mid-rise educational building by appropriate choice of materials, end-of-life and other variables

Reduced carbon offset period of almost
30 years

Based on the potential energy positive design of the case example

Increased role of buildings in mitigating
climate change

By reducing the carbon emissions from construction sector, climate change mitigation is foreseeable.