Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Architecture and Design
Department of Architecture and Technology

Ingrid Rasmussen

Exploring the Integration of Embodied Carbon Assessment in Architectural Design

An Analysis of Current Practices

Master's thesis in Sustainable Architecture
Supervisor: Eirik Resch
Co-supervisor: Patricia Schneider-Marin

May 2023

NTNU
Norwegian University of
Science and Technology

Ingrid Rasmussen

Exploring the Integration of Embodied Carbon Assessment in Architectural Design

An Analysis of Current Practices

Master's thesis in Sustainable Architecture
Supervisor: Eirik Resch
Co-supervisor: Patricia Schneider-Marin
May 2023

Norwegian University of Science and Technology
Faculty of Architecture and Design
Department of Architecture and Technology

NTNU
Norwegian University of
Science and Technology

Abstract

The material used in buildings is globally responsible for approximately 28% of the annual carbon dioxide emissions within the building sector. Tracking these embodied carbon emissions within a building project is done by conducting a life cycle assessment (LCA). The Norwegian building code TEK 17 will include an LCA for the finished project as part of the approval process from July 2023 and refers to stricter requirements in the future. With the importance of lowering embodied carbon in buildings on the table, the urgency of including embodied carbon considerations in the design process increases. Architects have a large influence on architectural designs and consequently on the environmental impact of buildings. However, as of now embodied carbon assessment is not well integrated into their design process. This study investigates the integration of embodied carbon assessment in architectural design.

A broad literature review about the design process in Norway as well as research about LCA of embodied carbon and related topics was conducted to investigate the current practice and provide an understanding of the topic. Five semi-structured interviews were conducted, with four architects and one engineer, to gain insight regarding work practices, project structures, choices during the design, and knowledge and perceptions regarding embodied emissions. Four interviews from the Voldsløkka school project, which is related to the research project ARV, were included in the interview analysis. Based on the insights gained in the interviews, various considerations related to embodied carbon and LCA calculations were explored in detail. These additional considerations provided further insights and address controversies and uncertainty identified during the interviews.

The interviews provided valuable insights into three key areas: the architectural design process and involved parties, integration of LCA into the design process, and embodied carbon considerations and influences. The supplementary investigation further delved into the use of simplified documentations and highlighted important aspects to consider in LCA calculations.

This thesis concludes that the integration of LCA into the design process is a developing field and with environmental aspects getting more attention the design process is evolving towards a more interdisciplinary process. Integration of LCA in the early design is crucial for a successful enhancement of the embodied carbon in buildings, but streamlined approaches and understandable guidelines need to be advanced further. Additionally, architects and other stakeholders must acknowledge that addressing embodied carbon is a complex and challenging task within an already compound design process. It requires effort and a broad understanding of the correlations between different aspects to take informed decisions. Simultaneously, researchers and engineers should strive to communicate LCA concepts in a more accessible manner, ensuring that architects are not overwhelmed by the vast amount of information and various calculation approaches.

Sammendrag

Materialene som brukes til bygninger står globalt for ca. 28 % av de årlige karbondioksidutslippene i byggesektoren. Sporing av disse innebygde karbonutslippene i et byggeprosjekt gjøres ved å gjennomføre en livssyklusvurdering (LCA). Den norske byggtekniske forskriften TEK 17 vil inkludere en LCA for det ferdige prosjektet som en del av godkjenningsprosessen fra juli 2023 og viser til strengere krav i fremtiden. Med viktigheten av å redusere det innebygde karbonet i bygninger på agendaen, øker naturligvis også behovet for å ta hensyn til innebygd karbon i designprosessen. Arkitekter har stor innflytelse på den arkitektoniske utformingen og dermed på bygningers miljøpåvirkning. Per i dag er imidlertid vurderingen av innebygd karbon ikke godt integrert i designprosessen. Denne studien undersøker hvordan livssyklusvurdering av innebygde karbonutslippene kan integreres i arkitektonisk design.

For å skaffe en god forståelse for temaet og dagens praksis ble det gjennomført et bredt litteraturstudie av prosjekteringsprossessen i Norge samt forskning på om og hvordan LCA av innebygd karbon og relaterte emner blir gjennomført som en del av byggeprossessen. Fem semistrukturerte intervjuer, med fire arkitekter og én ingeniør, ble gjennomført for å få innsikt i arbeidspraksis, prosjektstrukturer, valg under prosjekteringen samt kunnskap og oppfatninger om innebygde utslipp. Fire intervjuer fra skole-prosjektet Voldsløkka, som er relatert til forskningsprosjektet ARV, ble inkludert i intervjuanalysen. Basert på innsikten fra intervjuene ble ulike hensyn knyttet til innebygd karbon og LCA-beregninger utforsket i detalj. Disse tilleggsbetraktningene ga ytterligere innsikt og tok opp kontroverser og usikkerhet som ble identifisert under intervjuene.

Intervjuene ga verdifull innsikt i tre hovedområder: den arkitektoniske designprosessen og involverte parter, integrering av LCA i designprosessen, og hensyn til og påvirkning av innebygd karbon. Den supplerende undersøkelsen gikk nærmere inn på bruken av forenklet dokumentasjon og belyste viktige aspekter å ta hensyn til i LCA-beregninger.

Konklusjonen i denne studien er at integrering av LCA i designprosessen er et felt i utvikling, og i takt med at miljøaspektene får mer oppmerksomhet, utvikler designprosessen seg i retning av en mer tverrfaglig prosess. Integrering av LCA i den tidlige designfasen er avgjørende for en vellykket forbedring av bygningers innebygde karboninnhold, men strømlinjeformede tilnærminger og forståelige retningslinjer må videreutvikles. I tillegg må arkitekter og andre interessenter erkjenne at det å ta hensyn til innebygd karbon er en kompleks og utfordrende oppgave i en allerede kompleks designprosess. Det krever innsats og en bred forståelse av sammenhengene mellom ulike aspekter for å kunne ta informerte beslutninger. Samtidig bør forskere og ingeniører etterstrebe å kommunisere LCA-konsepter på en mer tilgjengelig måte, slik at arkitekter ikke blir overveldet av de store mengdene med informasjon og de ulike beregningsmetodene.

Acknowledgements

This master's thesis marks the end of my studies in Sustainable Architecture at NTNU. My deepest thanks go to my friends and classmates who went on this journey together with me. I am grateful to have found a group of people who I could work with on university projects and at the same have a personal relationship with outside of the studies. I hope that completing our master's does not mark the end of our friendship but only the beginning of a new chapter.

The last weeks and months have been an intense time, which I would not have managed without the support and understanding of my partner. I furthermore would like to express my gratitude to my family at home in Switzerland who gave me moral support from a distance.

Thanks need also to go to my supervisor Eirik Resch and co-supervisor Patricia Schneider-Marin, who helped me write this master's thesis with their professional knowledge and input. Additionally, I would like to thank Herman Rinholm from Reduzer for taking the time to support me with the usage of Reduzer and giving me a deeper understanding of the program.

Last but not least, I would like to thank the five interviewees for taking the time to answer my questions and giving me insight into their work, knowledge and opinions. The interviews are the main part of my thesis. Their answers and elaborations shined a new light on the topic and influenced my research and investigations.

Table of contents

List of figures

List of tables

List of abbreviations

AEC: Architectural, engineering and construction
BIM: Building information modelling
BREEAM: Building Research Establishment Environmental Assessment Method
BTA: *Bruttoareal* (Gross area)
BYA: *Bebygd areal* (Built-up area)
CO_{2eq}: Carbon dioxide equivalent
DFØ: *Direktoratet for forvaltning og økonomistyring*
(The Norwegian Agency for Public and Financial Management)
EDP: Environmental product declaration
EN: European Standard
ESL: Estimated service life
GHG: Greenhouse gas
GWP: Global warming potential
ISO: International Standards Organization
LCA: Life cycle assessment
NS: Norwegian Standard

1 Introduction

The construction sector consumes about half of all raw materials processed in the world and the construction, operation and maintenance of buildings globally uses about 50% of all resources (Hegger, et al., 2012). Within the building sector, 28% of annual carbon dioxide (CO_2) emissions can be attributed to material used in buildings (IEA & UNEP, 2018). The emissions over a building's life cycle can be divided into two types: the operational energy demand and the embodied carbon. While efforts have been made to optimize the energy consumption from building operations, the impact of construction and building material emissions have gained importance (Hollberg & Ruth, 2016).

In Norway, the national building code TEK 17 §17-1 will implement new requirements that mandate the inclusion of a life cycle assessment (LCA) as part of the approval process. This marks the first time that such requirements have been put in place. Notably, the LCA in this building code is a relatively straightforward assessment, and there are no explicit maximum requirements or limit values. Rather, the sole requirement is to submit an LCA as part of the documentation process. There is a recommendation to carry out studies from the early design stage and optimize the greenhouse gas (GHG) emissions throughout the design process, but no requirements other than for the final design are set. This implementation is meant to increase the knowledge of LCA in the building sector and prepare the involved parties for stricter regulations in the future (TEK 17, 2022).

Architects have a key role in the design and development of buildings. They look at buildings as a holistic system, work on the theoretical concept, create spatial sequences and qualities, and consider the practical use of the technical system and object (Hegger, et al., 2012). As regulations governing GHG emissions of buildings continue to become more stringent, it is increasingly important for architects to incorporate considerations of embodied carbon in building materials into their projects. Doing so can help ensure that buildings are designed with a lower carbon footprint and are better equipped to meet evolving environmental regulations.

Several studies highlight the significance of optimising the GHG emissions during the early stages of the design process, as this is when important decisions are made, and the costs of adjustments are minimal. Although the integration of LCA into the design process has the potential to significantly reduce embodied carbon and improve the environmental performance of buildings, it is not commonly utilized due to its perceived complexity and time-intensive nature (Hollberg & Ruth, 2016). Furthermore, architects lack intuition regarding the potential impact on the global warming potential (GWP) of different decisions taken during the design process (Basbagill, et al., 2012).

Software that calculate embodied carbon through LCA, such as Reduzer, are continuously evolving to provide a user-friendly interface that appeals to architects and their working methods. These programs also collect databases, allowing for faster and more accurate assessments and comparisons during the early design stages, as well as precise calculations in later stages. They aim to offer clear and transparent visual presentations of results to enhance users' understanding of the results and consequences.

While in the Norwegian national building code regulations regarding embodied carbon are slowly being implemented, certification actors like BREEAM-NOR and pilot programs like FutureBuilt are setting higher benchmarks towards the environmental impact of buildings. Voldsløkka school in Oslo is such a pioneer object. It is part of the research project ARV, which aims to demonstrate and validate attractive, resilient, and affordable solutions for the change towards a sustainable building industry (Lolli, et al., 2022).

While the knowledge regarding embodied carbon in building materials and the assessment of them over their life cycle increase, the question remains for how architects can integrate this into the complex design process.

1.1 Problem statement and thesis specification

Architects have a large influence on the design and planning process of a building project and are also often responsible for coordinating the development with all the involved parties. As environmental aspects get more and more attention in the building sector, the urgency to include these considerations in the design process increases.

As an architect, it is challenging to navigate the overwhelming amount of technical information related to GWP calculations and integrate embodied carbon considerations into the already complex building process. Lowering embodied carbon as a design driver is a new concept, and there are no clear guidelines on how to effectively integrate it into the design process. Moreover, it is not yet a mandatory part of general architectural education, which further complicates matters. Architects are trained to create enclosed spaces for people to use and inhabit. The focus is on proportions, expression, haptic, movement flows, and concepts. Integrating technical aspects into this conceptual and intuition driven process can be a challenge.

Currently, LCA considerations in construction are limited to a few pioneer projects. In order to reach the climate goals, the building sector needs to reduce its GHG emissions on a larger scale and more widely. Meaning more buildings need to start integrating LCA in the design. For this to happen, architects need to get the tools and knowledge to take the right decisions at the right time in the design process.

This master’s thesis is investigating the extent of architects' knowledge about embodied carbon in building materials, and how they currently integrate this knowledge into their work. To gain a broad understanding of the topic, this thesis examines the design process and interdisciplinary collaboration within it. This involves conducting five semi-structured interviews and comparing the findings with current practices and research. Four interviews done within the Voldsløkka school project are additionally incorporated to include practical knowledge from a pioneer project. The findings from the interviews are supplemented with considerations and calculations regarding embodied carbon of building materials to further explore the findings from the interviews.

1.2 Research questions and limitations

The following three research questions were articulated to lead the investigation of this study.

Research question 1:
How are architectural designs currently developed?

Research question 2:
(How) are LCA considerations of embodied carbon currently integrated into the design process?

Research question 3:
How can embodied carbon assessments be influenced in an architectural design process to improve the performance of the project?

Some limitations are present in this study and the possible findings. The design process of every project is unique due to an endless number of different factors, which could be project size, function of the building, the client and economical structure, and different focuses within the project. This leads to a large variety of approaches used by architects to start and develop a design. Aspects like spatial quality, integration in the context, tradition and preferences by the client, user, and planner are important for an architectural project and its development, but it is also difficult to justify them numerically and weigh them against calculated GHG emissions. Furthermore, the lack of knowledge about the consequences of certain decisions and actions in the present and future need to be included in the considerations.

Interview-based research often faces criticism regarding the limited generalizability of findings due to small sample sizes. However, semi-structured interviews allow for a deep-dive into the subjects' knowledge, which was considered to be of large value for this study. Although the interviewees had a pre-existing interest in integrating environmental aspects into their projects, their knowledge about LCA varied.

This thesis is focusing on the Norwegian building industry, design process and LCA context. There are international understandings of design processes and embodied carbon considerations, as well as national aspects. The differentiation between national and international contexts would go beyond the feasible scope of the master's thesis.

2 Background

This chapter gives background information to different parts of the thesis. It gives information about the design and planning structure and presents the main standards, guidelines and frameworks related to this topic. The framework of LCA of embodied carbon is presented and background information on the topic of GWP, GHG emissions and their related calculations and assessment is given. Furthermore, the chapter gives information about the integration of embodied carbon considerations into the design process and how optimization influences architecture and building designs.

Norwegian terms whose translation might cause a misleading understanding or confusion are kept in Norwegian and marked in *italic*. To ensure transparency regarding translation are the original terms from translations in brackets in (*italic*).

2.1 Structure of the design and planning process

The design and planning process is not a linear workflow executed by one party but is more complicated and intertwined. There are various ways to structure a design process of a building. In Europe, some of the more known ones are the RIBA Plan of Work from the United Kingdom and the HOAI Leistungsphasen from Germany. Bygg21 and *Direktoratet for forvaltning og økonomistyring* (DFØ, The Norwegian Agency for Public and Financial Management) provide guidelines which are used to structure the design and building process in Norway.

There are also ways to structure the building elements and the information produced in the design process. Norwegian Standard (NS) 3451 structures the building elements in Norway. Building information modelling (BIM) is a digital way to communicate information about a building digitally between the architectural, engineering and construction (AEC) professions.

2.1.1 Design process in Norway

In Norway, there are different ways of structuring a design process, as it is highly dependent on the project and the involved parties. However, there are actors like Bygg21 or DFØ which provide guidelines and frameworks giving an overview of the stages required in a building process in Norway (DFØ, 2022; Grønn Byggallianse, 2020).

Bygg21's framework *Neste Steg* structures the project development into eight stages.

1. *Strategisk definisjon* - Strategic definition
2. *Program- og konseptutvikling* - Programme and concept development
3. *Bearbeiding av valgt konsept* - Processing of the selected concept
4. *Detaljprosjektering* - Detailed design
5. *Produksjon og leveranser* - Production and deliveries
6. *Overlevering og ibruktakelse* - Handover and commissioning
7. *Bruk og forvaltning* - Use and management
8. *Avvikling* – Decommissioning (Bygg21, 2023)

Stages two to four are of particular importance for architects and planning teams, as this is when they are primarily involved in the design process. In the second stage, different programmes and concepts that meet the needs defined in the first stage are explored. Various analyses and conceptual studies should be carried out in this stage to identify the best conceptual solution. Furthermore, it is decided whether to proceed with the project. Preliminary specifications of scope, cost, and quality together with the overall implementation strategy are determined. The objective of this stage is to establish whether the measure is feasible and determine the most appropriate conceptual solution for the project.

In the third stage, the selected concept from the second stage is further developed and detailed. The building brief is detailed to a room level and drawings and models define the most important aspects of the project. Calculations are becoming more detailed, and the quality of the project is assured. The chosen solutions are reviewed to ensure the feasibility of the project. In a collaborative contract, this stage is used to jointly develop the project. In the case of a turnkey contract, the contractor is awarded based on the results of this stage. The objective of this stage is to develop principles for the technical solution, realistic strategies, and plans for action so that final decisions on implementation and financing can be taken on a solid basis. This stage normally presents the last possibility to cancel a project.

In the fourth stage, documents and drawings for production are prepared. In a construction contract, the submittals are finalised as BIM-model or descriptions and drawings, that form the basis for the contractor's quotation. Ideally, these drawings are detailed enough to start construction, although adjustments may need to be made to match the contractor's choice of equipment and methodology. In a turnkey or joint venture contract, the construction documents are prepared in close cooperation with the subcontractors and suppliers. In turnkey contracts, the responsibility for coordination is left to the main contractor. The objective of this stage is to produce the required details and documentation to guarantee a safe and correct execution of the building project (Grønn Byggallianse, 2020).

DFØ lists five steps in a building process (*Byggeprossesen)*. The second and third stages from Bygg21 are represented in the second stage of DFØ. Furthermore, the last two stages from Bygg21 are not considered in the building process.

1. *Avklare behov* - Clarify needs
2. *Konseptutvikling og -bearbeiding* - Concept development and processing
3. *Detaljprosjektering* - Detailed design
4. *Utførelse* - Construction
5. *Overlevering* - Handover

In the second stage of DFØ's building process, *Skisseprosjekt* (conceptual design) and *Forprosjekt* (schematic design) are developed. The conceptual design is described as the phase where first calculations and drawings that realise the project programme are made. With that, the basis for the architecture and design is laid. The finished conceptual design should concretise and verify the requirements and needs of the project, as a basis for the final decision on investment. This decision is supported by cost calculations, outlined solutions for construction methods, technical guidelines and financing plans. In the schematic design, the functional and physical structure of the concept design will be further developed. User and technical requirements must be at a sufficiently detailed level to define the scope, budget, and qualities. The programme is detailed to room level and solutions are verified. The project needs to be brought to a level of detail which enables a confident decision that the project can be realised and implemented. Models and drawings representing the main choices for the project are created. The project owner should clarify the impact of the intervention and confirm the contract strategy, including the selection and prioritisation of management parameters. This provides the basis for the final decision on investment, costing, financing plan, contractual and organisational structure, and is the basis for an updated contract strategy. A decision to proceed with a project will usually mean that the application process for a building permit is started. The detailed design can then proceed in parallel with the permit processing by the planning and building authorities in the municipality (DFØ, 2022).

BREEAM-NOR refers in its guideline to Bygg21's *Neste Steg* and links each relevant issue in its certification protocol with the applicable step in *Neste Steg*. They furthermore specify when in the process the terms *Skisseprosjekt*, *Forprosjekt* and *Detaljprosjekt* are applied (Grønn Byggallianse, 2020).

Figure 2.1 shows the previously described planning and design processes and set them in relation to each other.

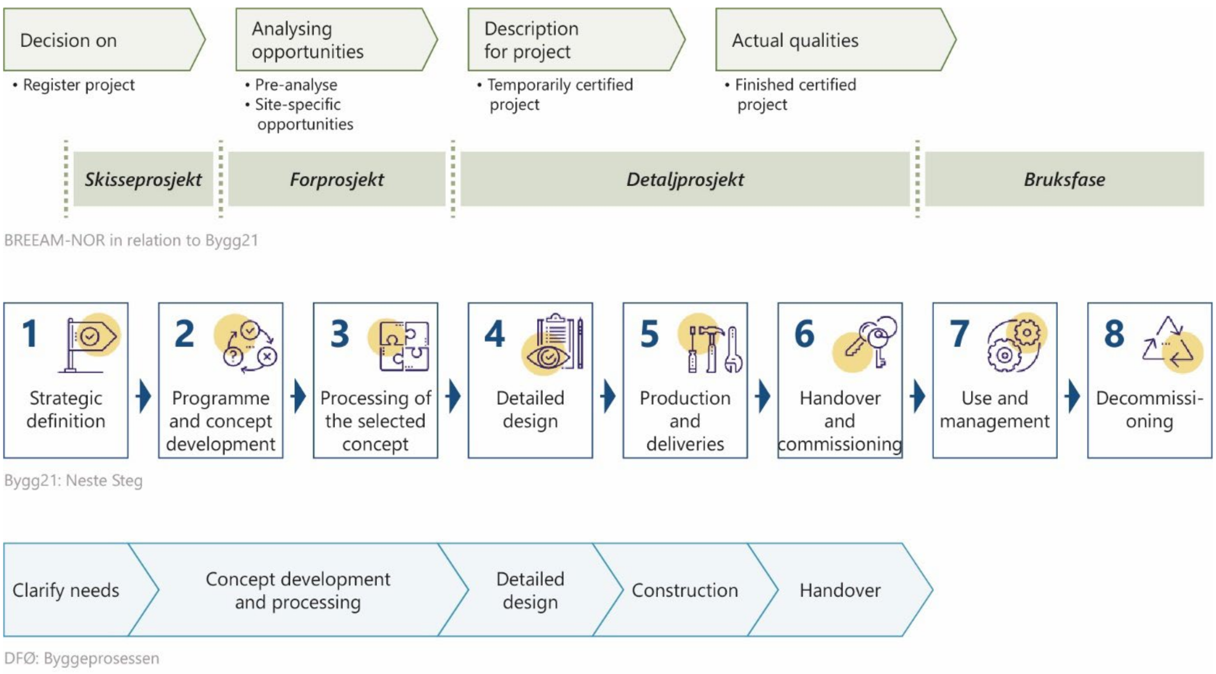


Figure 2.1: Comparison of the planning and design process according to BREEAM-NOR, Bygg21: Neste Steg, and DFØ: Byggeprossesen.

Graphic created by author based on (Bygg21, 2023; DFØ, 2022; Grønn Byggallianse, 2020)

2.1.2 Involvement of different players in the design process

The development of a building project is an interdisciplinary task that involves different players responsible for the design and planning process as a group. The extent of involvement varies depending on the project's characteristics, such as its structure, size, goals, and other relevant factors. (Hegger, et al., 2012).

Politicians and authorities set standards and have due to that a large influence on the environmental impact of the building industry. Urban and regional planners have a considerable influence on land use for buildings and infrastructure. Clients, whether individuals or institutions, are the initiators of designing and building activities and can set requirements and demands for the project, significantly impacting its environmental impact. Factors like longevity, adaptability and low running cost are key issues for the client and operators. The profile of architects is changing from a universal planner to that of a coordinating team leader, due to the rising demand for holistic building concepts. During the design process, the architect is involved in most decisions and assists the client to navigate the different choices possible. Although many planners recognize the need to integrate environmental aspects into construction, they may lack relevant detailed knowledge and assertiveness to advocate for sustainable solutions. Engineers and consultants bring specialized knowledge and expertise to the design process and can help find the best solutions for the project as a holistic object. This requires intensive discussions among the interdisciplinary participants, best done from an early stage. Engineers and consultants who may contribute to the design process include structural engineers, mechanical, electrical, and plumbing (MEP) engineers, energy consultants, acoustics engineers, and fire protection experts, among others. (Hegger, et al., 2012).

With sustainability becoming more important and the design process becoming more complex, there is also a change in the involvement of the different players. Figure 2.2 visualises this change by showing the predicted involvement of players in the future (Hegger, et al., 2012). While engineers, facility managers, and energy consultants become earlier involved in the process is the environmental consultant not mentioned in this graphic form 2012.

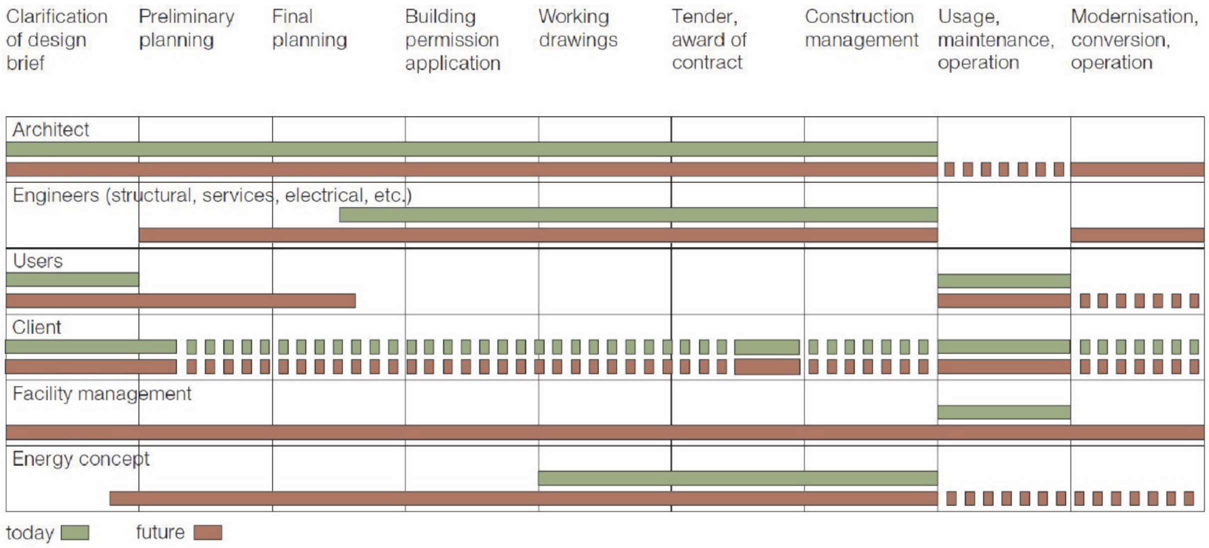


Figure 2.2: Players in the planning and usage processes, today and in the future.
Graphic edited by author based on (Hegger, et al., 2012)

2.1.3 Use of BIM in the design process

Over the years the working and drawing tools for architects and engineers have undergone large change. There has been a technological development from hand drawings to 2D computer-aided design (CAD) over to 3D component-based drawings. BIM is a further development of the three-dimensional drawing, and is used for model analysis, clash detection, product selection, and whole project conceptualization. In simple terms: CAD + specifications = BIM. The aspect of BIM which needs to be emphasized is "building information". Where CAD mainly helps to design or draft a project with a computer tool, BIM includes additional information and improves the extraction and sharing of this information. With BIM more project participants can be involved, and the information exchange is improved (Weygant, 2011). Industry foundation classes (IFC) is the data format to share BIM data among software applications (ISO 16739, 2018). Drawing programs like Revit, ArchiCAD, and Vectorworks support BIM and are able to import and export projects to IFC files.

Integrating LCA into the design process with the help of BIM is seen as a promising solution. It simplifies a complex and labour-intensive process and can support the decision-making process. The data exchange between BIM and LCA calculation tools remains a challenging issue. The vast majority of BIM-based LCA studies are conducted using a manual or semi-automatic input method (Fnais, et al., 2022). A survey from Germany indicates that the adaptation to the new possibilities offered by BIM is still ongoing and that different measures have many different potentials. While the use of BIM in combination with LCA for sustainability certifications seems to be an established practice, the use for planning optimization purposes is still under establishment (Schumacher, et al., 2022). Hollberg & Ruth (2016) see the challenge of BIM-integrated LCA in the high complexity that a BIM model can achieve. While smaller projects often do not employ BIM at all, it is a means to manage larger projects. Due to the complexity of BIM models, the likelihood of creating various design proposals and optimizing the embodied carbon in building materials with its help is limited. Applying BIM in the crucial early design is therefore not practical (Hollberg & Ruth, 2016).

2.1.4 Structure of the building elements

The system for subdividing a building into construction elements for systematisation and classification is defined in NS 3451. In addition to its application in building specifications, statistics and knowledge transfer regarding costs, properties, and duration, the subdivision approach is also valuable for discussing GHG emissions of building elements and preparing quantities for calculation in drawing programs. (NS 3451, 2022). The standard is referenced in guidelines like TEK 17 and BREEAM-NOR and builds the structure for the building elements in Reduzer.

The standard divides the building into (2) Building, (3) HVAC installations, (4) Electrical power, (5) Telecommunication and automation, (6) Other installations, and (7) Outdoors. For architects and their involvement in the project, the (2) Building is the most important one.

(2) Building is further divided into:

(20) Building, general
(21) Ground and foundations
(22) Load-bearing systems
(23) External walls
(24) Internal walls
(25) Slabs
(26) Roof
(27) Fixed inventory
(28) Stairs, balconies, etc.
(29) Other building parts

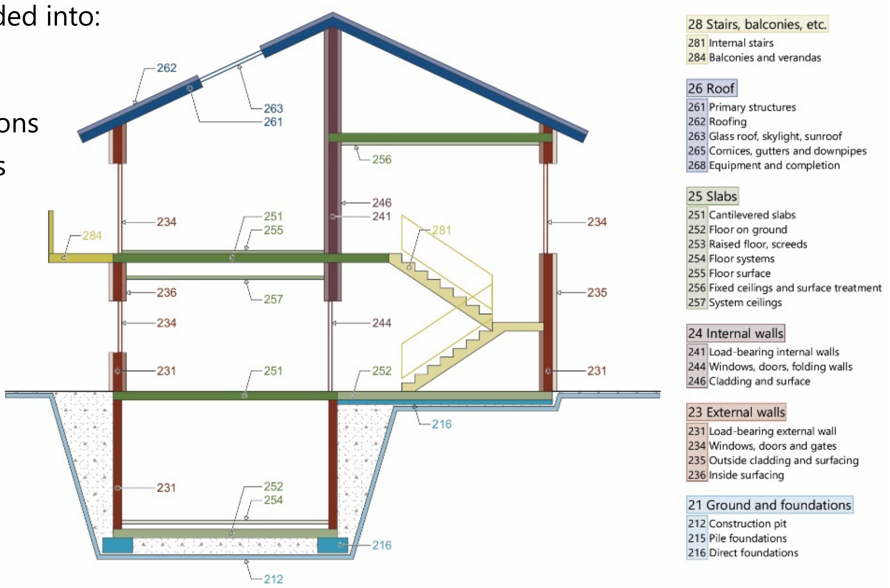


Figure 2.3 shows the main elements of a simplified building.

Figure 2.3: Building elements according to NS 3451.
Graphic created by author based on (NS 3451, 2022)

Important to point out is that the (22) Load-bearing systems are only separate systems that are not an integrated part of walls, roofs or slabs. If the elements of the load-bearing system of a building can also be defined as an external or internal wall, a slab or a roof, the element will be systemized under (231), (241), (251) respectively (261) (NS 3451, 2022).

2.2 Embodied carbon of buildings

Embodied carbon of a building refers to the CO_2 equivalent emissions generated during all stages of a building's life cycle. Material extraction, manufacturing, transportation, installation, maintenance, demolition, and disposal all contribute to the emissions. This concept is depicted in Figure 2.4. To quantify these emissions, a method called LCA is used, which tracks the emissions produced over the full life cycle of a product, process or building and gets expressed as the GWP in kilograms or tonnes CO_2 equivalent (Carbon Leadership Forum, 2020).

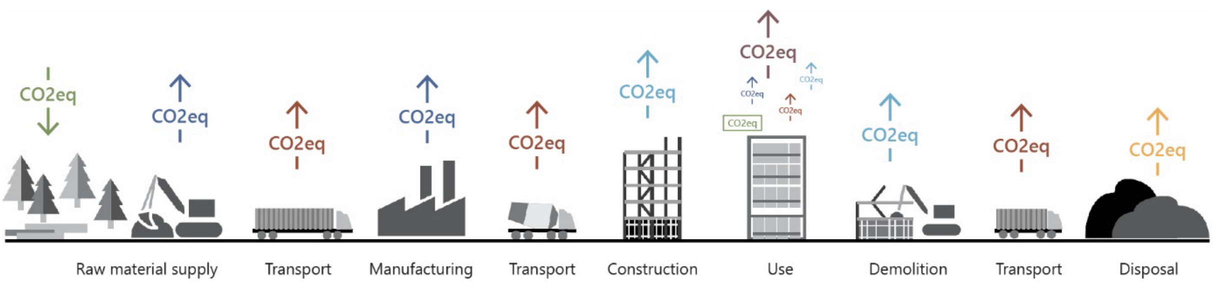


Figure 2.4: Illustration of the life cycle of building materials and the connected stages where embodied carbon is emitted.
Graphic edited by author based on (Carbon Leadership Forum, 2020)

2.2.1 LCA principles and framework

Over the years International Standards Organization (ISO) 14040 has become the most common standard for life cycle assessment (LCA) and a Norwegian translation can be found in the standard NS-EN ISO 14040. This standard defines the LCA framework which is depicted in Figure 2.5. It is important to note that the LCA framework is not building industry-specific but a general guide on how to structure LCA.

The framework consists of four steps:

(1) Goal and scope definition
(2) Inventory analysis
(3) Impact assessment
(4) Interpretation

(ISO 14010, 2006)

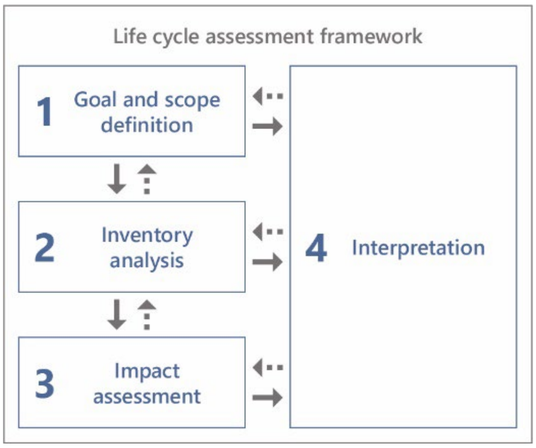


Figure 2.5: Life cycle assessment framework according to ISO 14040.
Graphic created by author based on (ISO 14010, 2006)

Defining the goal and scope of an LCA is the initial and crucial step, as it determines the purpose and methodology of the assessment. Doing so helps to direct the efforts and provide meaningful analysis which meets the set goals. In the context of the design process, there are numerous potential goals for conducting an LCA. One objective of an LCA can be to assist in decision-making by comparing design options, materials, or building systems. Another objective for an LCA can be the evaluation of the completed design or building object. The assessment can be used to be benchmarked against predetermined goals and standards or as documentation of the environmental performance for reporting and accountability purposes. When defining the goals, it is beneficial to consider the audience or recipient of the assessment. This allows for customization and alignment with their knowledge, and expertise, ensuring an efficient and understandable communication of the assessment.

The scope defines the extent of the assessment, outlining the included and excluded considerations. It covers a wide range of topics and increases the transparency and comparability of the analysis. A comprehensive scope needs to define, the functional equivalence, the reference study period and the system boundary. Functional equivalence describes the key functions of an object and the units it is measured with. The information provided enables a consistent and meaningful comparison between different objects and assessments. The reference study period defines the time horizon, usually measured in years, in which the building is studied. It is often synonymous with the estimated service life (ESL) of a building. The system boundary sets the parameters of the analysis by defining the included building elements, life cycle stages, and environmental impacts (Huang, 2019). Predefined calculation methods ensure an objective comparison of different objects and simplify the setting of the scope. Herby is important to keep in mind that the data for the set scope must be available, reliable and integrated into the assessment.

The second step is to collect the inventory. The data collection can be relatively straightforward or complex depending on the available information, the building, and the scope of the LCA. The inventory comprehends information about materials, and quantities, but should also include information about transport, water consumption, energy usage and so on. Tools such as BIM for determining the quantities and LCA tools may be helpful. Defining the material has a major influence on the assessment outcome. It is possible to use industry-average data or product-specific data (Huang, 2019). Environmental product declarations (EPDs) are LCAs of building products which can be used in more holistic assessments. They summarize the environmental profile of a component, a finished product, or a service in a standardized and objective way (The Norwegian EPD Foundation, 2023). Assumptions regarding transportation distances, construction methods, replacement and refurbishment, operational energy and water usage, and end-of-life are called scenarios and give the baseline for inventories where quantities and information are not easily available. Some LCA tools provide default values for scenarios such as transport. These should be transparent to the user of the tool (Huang, 2019).

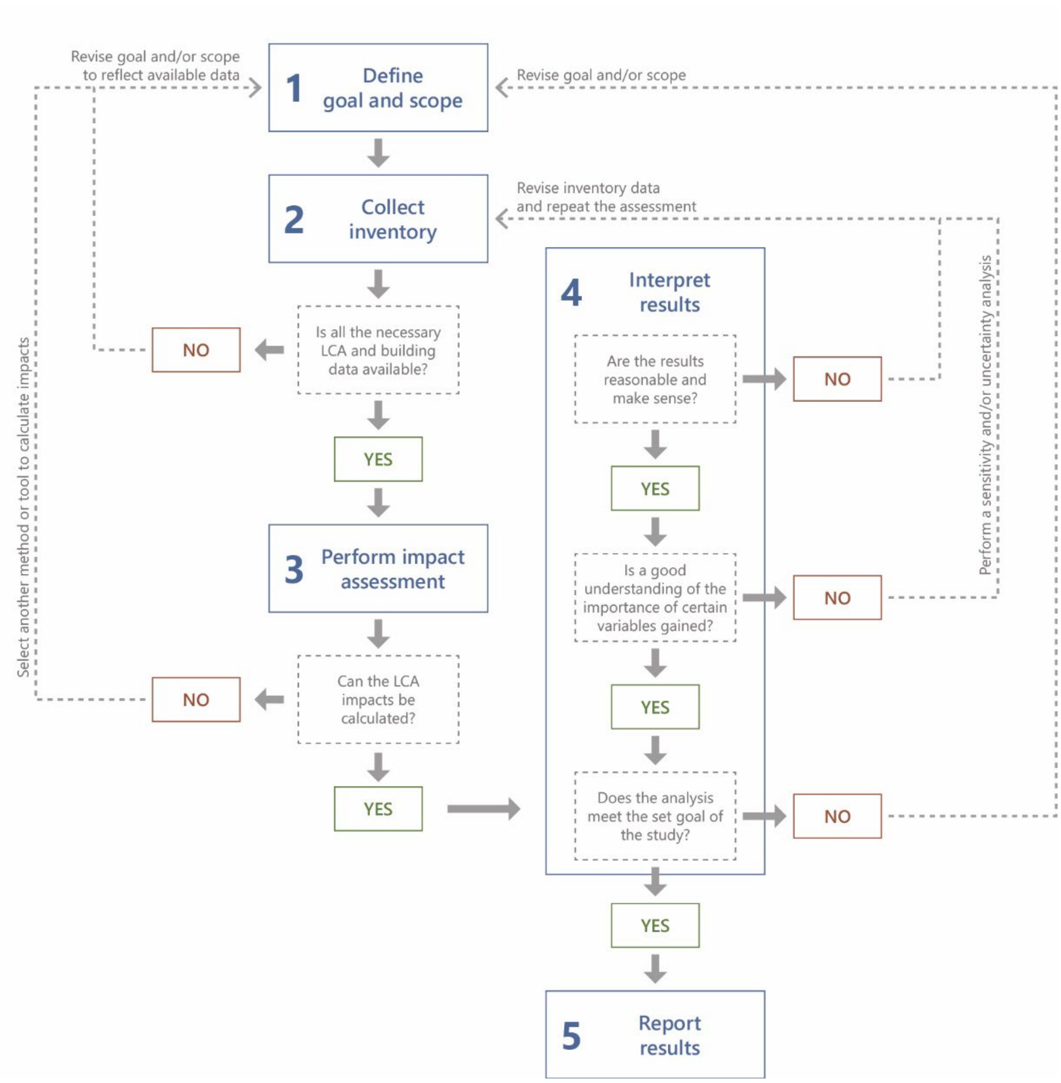


Figure 2.6: Flow chart to visualize the steps of a building LCA.
Graphic created by author based on (Huang, 2019)

The third step is to calculate the environmental impact of the building based on the set goal and scope and with the data collected in the inventory. The calculation can be performed with the help of an LCA calculation tool (Huang, 2019).

Interpreting the results is the fourth step in LCA. This means understanding the results beyond the simple number and includes investigating questions like: "What do the results mean for the study?", "Are the results plausible?", and "What conclusions can be drawn?". Depending on the goal of the LCA different ways of visualizing and grouping the results can help to analyse and interpret the results more effectively (Huang, 2019).

During the process of an LCA different challenges can cause a revision of previous steps. The float chart Figure 2.6 can be used as a guideline through the LCA process.

2.2.2 GHG calculations for buildings

A full LCA of a building includes a large variety of factors, which depend on the set goal and scope of the LCA. Looking only at embodied carbon of a building over its lifetime narrows down the included elements and life cycle stages.

The life cycle stages of a building are presented in European standard (EN) 15978 and referenced by NS 3720. Not all stages are necessarily included in an assessment, as some may have minimal impact on the overall results, while others may be excluded due to a lack of reliable data. Stages A1-A5, B1-B5, and C1-C4 account for the embodied carbon, while stage B6-B8 account for the operational impacts. The life cycle stages according to EN 15978 are depicted in Figure 2.7.

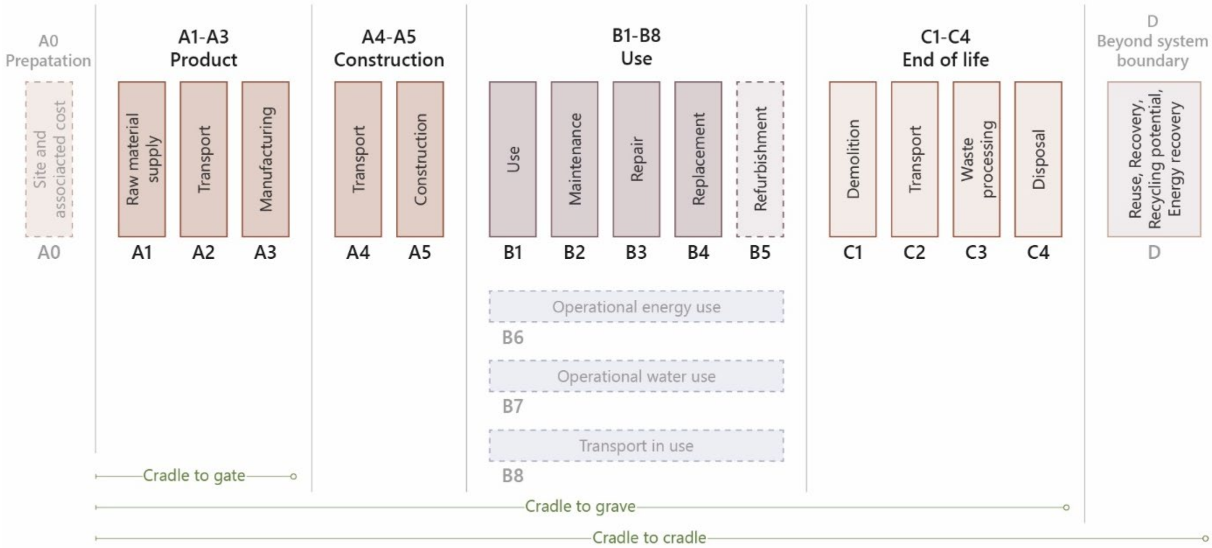


Figure 2.7: Building's life cycle stages according to EN 15978 with the stages most important to embodied emissions highlighted.
Graphic created by author based on (EN 15978, 2011)

The product stage (A1-A3), also called cradle-to-gate, describes the GHG emissions emitted during the production of the material. This information can be retrieved from EPDs and is presented as the GWP per specific unit, for example, kg, m^3, or m^2. Looking at the timeline those emissions happened in the past. They can be influenced by material choices and optimization in quantities required for the building.

A4 adds GHG emissions caused by the transport of the material from the factory gate to the building site and A5 accounts mainly for the GHG emissions due to cuttings and waste at the building site, but also includes energy consumption for construction. Those emissions are caused in the present and can be influenced by choosing locally sourced materials with little waste and optimising the building process.

The use stage (B1-B5) accounts for GHG emissions which will be caused within the ESL. These greenhouse gases have not been emitted yet but are expected to get released in the future due to use (B1), maintenance (B2), repairs (B3), and replacements (B4) of materials and building elements. This stage would also include refurbishments (B5), but as this is hard to predict they are usually excluded from the assessments. NS 3720 (2019) states that, if a building is refurbished and the refurbishment has not been calculated in any previous assessment, a new LCA should be carried out. Use (B1) is mainly containing the biogenic carbon uptake and cement carbonation, which are expressed in the form of negative numbers. B1-B5 can be influenced by designing details allowing for maintenance, and replacement as well as supporting the longevity of the materials. When choosing materials with longer ESL the frequency of the replacement is lowered and with that, the GHG emissions caused by new materials are saved.

The end-of-life stage (C1-C4) accounts for GHG emissions which are expected to occur in the far future when the ESL is reached. To ensure transparency for the assessment, scenarios are determined in the system boundaries. According to EN 15978 (2011), these scenarios shall only model processes that have proven to be economically and technically viable.

Stage D is most often considered to be beyond the system boundaries but reported as additional information and is accounting for reuse, recovery, recycling potential, and energy (EN 15978, 2011). The scenario for D is, similar to the B and C stages, difficult to predict and influence, as the potential environmental benefits or loads would happen far into the future.

2.2.3 Biogenic carbon uptake

Biogenic carbon is the carbon stored within the mass of bio-based products, such as timber, hamp, and straw. In the literature, three different models to account for biogenic carbon uptake and release in buildings are identified: the 0/0 approach, the -1/+1 approach, and the dynamic approach,, depected in Figure 2.8 (Hoxha, et al., 2020).

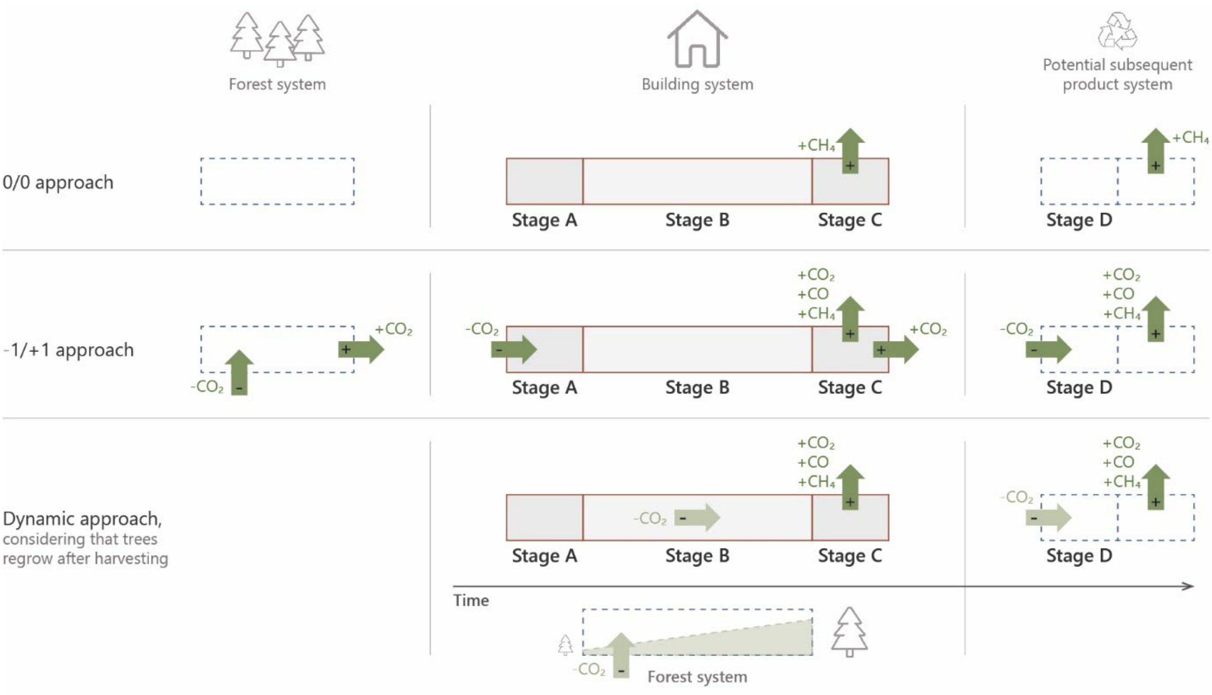


Figure 2.8: Illustration of the three different approaches to model biogenic carbon uptake and release. Dotted lines indicate the product systems that fall outside the building system boundaries.
Graphic created by author based on (Hoxha, et al., 2020)

The 0/0 approach, also referred to as carbon neutral approach, assumes a balance between CO_2 uptake during biomass growth and CO_2 release at the end-of-life stage. Consequently, there is no need to consider biogenic carbon uptake or release. Biogenic methane (CH_4) is modelled at the end-of-life, as biogenic methane has a higher impact on the GWP compared to biogenic carbon.

The -1/+1 approach tracks all biogenic carbon flow over a building's life cycle and provides an overview of all biogenic carbon flows. Within each system, the balance of biogenic carbon uptake and release is supposed to be zero. This approach contains the risk of misleading and biased results when only parts of the building system are assessed.

Correctly done the 0/0 and -1/+1 approach have the same final result, but with different interpretations. The main criticism of these two approaches is that they do not include considerations regarding the rotation periods related to biomass growth. Excluding this gives a wrong impression of carbon neutrality, especially when looking at shorter time horizons.

The dynamic approaches better capture the impact of time regarding the biogenic carbon release and the gradual uptake of carbon by the forest. Two scenarios can be considered. Scenario one assumes a growing of the trees before the use of the harvested timber. Scenario two assumes that the harvested trees are replaced with new trees which start growing right after the production process (Hoxha, et al., 2020). The latter is depicted in Figure 2.8.

According to Hoxha, et al., (2020), the dynamic approach to evaluating biogenic carbon uptake is the most robust and transparent one, due to the consideration of the forest rotation time and time aspects.

2.2.4 Building codes and guidelines connected to embodied carbon

Numerous building codes, certification labels, and guidelines addressing the evaluation, and regulation of embodied carbon and their assessment exist. Standardizing the assessment methods helps to create comparable calculations, which include the same considerations, uncertainties, and scope.

In countries like France, the Netherlands, and the other Scandinavian countries Denmark, Sweden, and Finland carbon footprint reduction criteria for embodied carbon in products are in place (Attia, et al., 2021). In Norway, the newly implemented national building code TEK 17 §17-1 requires a simple LCA as part of the approval process for all residential blocks and commercial buildings (TEK 17, 2022). Notably, this marks the first time that such requirements have been put in place in Norway. The LCA in this building code is a relatively straightforward assessment, carried out for the final design, with no explicit maximum requirements or limit values. Rather, the sole requirement is to submit an LCA as part of the documentation process. A recommendation to carry out studies from the early design stage and optimize the GHG emissions throughout the design process is integrated, but no binding requirement is set. TEK 17 §17-1 considers the life cycle stages A1-A3, A4, B2, B4 and the waste collected at the building site which is part of A5. The building code sets the ESL of the building to 50 years and considers the building elements 215 or 216 and 22, 23, 24, 25, 26 from NS 3451. The regulation is excluding biogenic carbon uptake by bio-based materials during growth from its scope. Generic (average) data can be used if no specific EDP exists but will lead to a 25% increase in GHG emissions. This implementation is meant to increase the knowledge of LCA in the building sector and prepare the involved parties for future stricter regulations (TEK 17, 2022).

NS 3720 gives the general framework for calculating GHG emissions in Norway. It defines four predefined scopes for overall calculations of GWP, where the basic without location requires the smallest amount of knowledge. At a minimum, the stages A1-A5, B1-B6, and C1-C4 need to be included. Stage D is added if possible. The ESL for a building is set to 60 years if not defined differently. The standard refers to NS 3451 for the structure of the building elements and includes all elements in 2 Building and 49 Other electrical power installations (e.g. PV panels). A full LCA includes all products unless they are presented in small quantities. The omitted products must be less than 5 per cent by weight of the building's total weight at a 2-digit element level (NS 3720, 2019).

FutureBuilt is a voluntary program for environmentally ambitious buildings which aims for high-quality architecture while lowering the carbon footprint by at least 50% compared to a reference building. The reference building is based on current national building regulations and common practices. Figure 2.9 illustrates how the regulation gets stricter over time to ensure FutureBuilt's leading position in low-carbon construction over time. It is developed specifically for the Norwegian market and includes the dynamic calculation method for GHG emissions FutureBuilt Zero v2. This is used to evaluate the carbon footprint and is based on NS 3720, but incorporates methods to account for technological weighting, the timing of emissions, biogenic carbon from wood products, carbon release from waste incineration of plastic and wood products, carbonation of cement products, and reusability in a circular economy (Resch, et al., 2022).

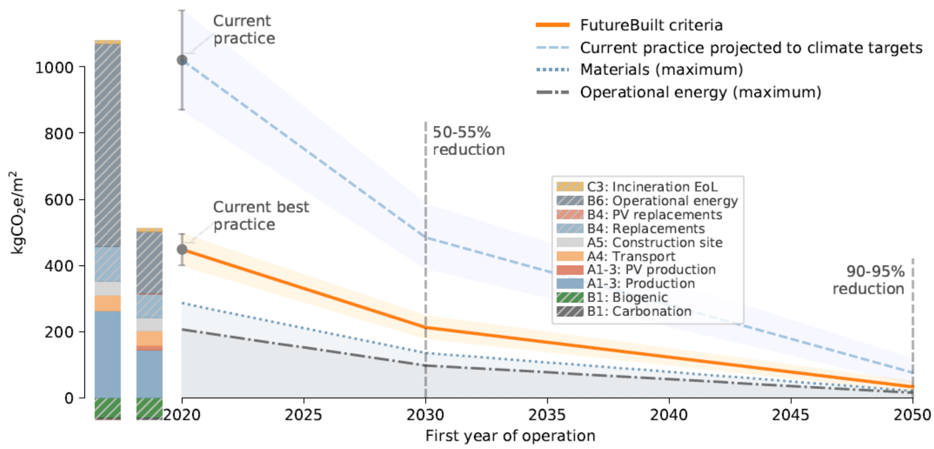


Figure 2.9: FutureBuilt Zero maximum emissions for a building's contribution to global warming over its lifetime at the time of commissioning.
(Resch, et al., 2022)

BREEAM is an acronym for Building Research Establishment Environmental Assessment Method and the oldest and worldwide most used certification system for sustainable construction (BauNetz, 2023). *Grønn Byggallianse* (Norwegian Green Building Council) has developed together with BREEAM a certification system which is adjusted to the Norwegian construction industry called BREEAM-NOR. The building gets evaluated in categories like management, health and wellbeing, energy, transport, water, materials, waste, land use and ecology, pollution, and innovation. The rating is divided into five benchmarks with Outstanding being the best one followed by Excellent, Very good, Good, and Pass. BREEAM-NOR can not be added at the end of the project but should be integrated into the design and development process. For this, it references the Bygg21 *Neste Steg* planning structure and gives guidance on when in the project certain decisions and considerations should be taken. The assessment criteria require a GHG calculation for the whole building life cycle, as well as a GHG budget in the early phase (stage 3). The objective of this approach is to establish climate objectives and identify strategies to mitigate GHG emissions, taking both short- and long-term perspectives into account. The early stage GHG calculation must adhere to NS 3720 and is required to include the building elements 21, 22, 23, 24, 25, 26, 28, and 49 according to NS 3451. Additionally, BREEAM-NOR's early-stage calculation requires consideration of life cycle stages A1-A3, A4 and B4. It is left to the user whether to use the FutureBuilt Zero method and its dynamic LCA approach. (Grønn Byggallianse, 2022).

Table 2.1 compares the different previously introduced standards and calculation methods regarding their scope and calculation approach.

	TEK 17	NS 3720*	FutureBuilt Zero	BREEAM-NOR**
EN 15978 stages	A1-A3, A4, (A5), B2, B4	A1-A5,B1-B5, C1-C4, (D)	A1-A5, B1-B5, C2-C3, D	A1-A3, A4, B4
NS 3451 elements	215 or 216, 22 - 26	20 - 29, 49***	21 - 29, 49***	21 - 28, 49***
ESL building	50 years	60 years	60 years	60 years
Dynamic LCA	No	No	Yes	Open / both
	*NS 3720 basic, without location, ** BREEAM-NOR early stage, *** (other electrical power installations)			

Table 2.1: Comparison of TEK 17, NS 3720, FutureBuilt zero, and BREEAM-NOR early stage regarding their scope for GHG calculations.
(Grønn Byggallianse, 2022; NS 3720, 2019; Resch, et al., 2022; TEK 17, 2022)

2.2.5 Tools for embodied carbon assessment

On the market, there is an increasing variety of tools, calculation programmes, and visualization documents from different actors available.

DFØ, for example, provides a very simple LCA calculation tool in the form of an Excel file, where the only required information needed to fulfil the calculation is the building type, the quantity of *bruttoareal* (BTA, gross area) above ground, the quantity of the BTA for heated and unheated basement, the *bebygd areal* (BYA, built-up area), and the depth of the foundation (DFØ, 2022). It gives a basic estimate for the different life cycle stages as well as an overall value for an ESL of 60 years. Furthermore, it gives recommended framework values for a basic, advanced, and ambitious goal. According to DFØ (2022), the tool is meant to set up an emission framework, which can be used in conjunction with requirements for GHG calculations in construction procurement.

The variety of building-specific LCA tools and calculation programs has increased in recent years. Programs like SimaPro, GaBi Software, and openLCA are developed to carry out LCA calculations, but they are not developed specifically for the building industry.

OneClick LCA is an LCA & EPD software adjusted specifically to the need of the construction industry (Ecoinvent, 2023). The program has an international database also including EPDs from EPD Norge. Furthermore, it is adjusted to the Norwegian building industry and includes predefined calculation method settings for NS 3720, TEK 17, and BREEAM-NOR (OneClick LCA, 2023).

LCAbyg is a freely available LCA calculation tool developed for the Danish building sector. It aims to present the complex results of a building LCA transparently. This provides an understanding of the impacts related to the building life cycle, and the environmental consequences of choosing different construction types and materials for the program users (Birgisdottir & Rasmussen, 2019). With LCAbyg-NOR the tool has been adapted to the Norwegian building sector.

Reduzer is a cloud-based web application to conduct LCA of construction projects, according to different Norwegian standards and calculation methods. It includes tools to plan for emission reduction and efficient material use while automating documentation and certifications (Research Council of Norway, 2023). Reduzer is still under development and only available to a selected few, amongst other students enrolled in the master's program Sustainable Architecture at NTNU and an increasing number of Norwegian companies.

OneClick LCA, Reduzer, and LCAbyg are able to perform detailed LCA requiring vast quantities of input, as well as providing simplified models and comparisons. Nevertheless, access to the tool is required and some skills in navigating the program are needed.

Documentations that visually present the GHG emissions of different materials in a comparable manner can be a more accessible approach to understanding the environmental impact of these materials. The Construction Material Pyramid (CINARK - Centre for Industrialised Architecture, 2023), Unboxing Carbon - the Catalog (Henning Larsen, 2022), and *Grønn Materialguide* (Green Material Guide) (Context AS & Grønn Byggallianse, 2021) visualise the emissions in different ways and detail. Table 2.2 gives an overview of these guidance tools, which can be useful for architects to get a general understanding of the impact of different materials. This can especially be useful in the early design phases.

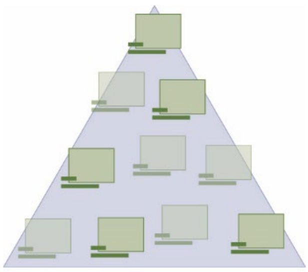
	Construction Material Pyramid	**Unboxing Carbon - The Catalog**	***Grønn Materialguide***
Country	Denmark	Denmark	Norway
Year	2023	2022	2021
LCA stages	A1-A3	A1-A3	A1-A3, B4
Data source	EPDs, if possible industry data	Product-specific EPDs	Several EPDs for one material
Study period	Material ESL	Material ESL	60 years
Functional unit	Material per m^3, Material per kg, According to the declared unit	Element per m^2	Element per m^2, Insulation per R=1
Sorting system	Material base with the possibility of sorting some functions	Function of material	Function of material
Preview			

Table 2.2: Comparison of the Construction Material Pyramid, Unboxing Carbon, and Grønn Materialguide regarding their data and scope.
(CINARK - Centre for Industrialised Architecture, 2023; Context AS & Grønn Byggallianse, 2021; Henning Larsen, 2022)

These documentations only include A1-A3 of the material as the other stages are more building object specific values. They visualize EPDs and make the comparison within each documentation easier. Direct comparisons between the different documentations are not possible without some caution, as they differ slightly in what they include and how they present it. Considering how time-consuming it is to directly compare EPDs, documentations like the Construction Material Pyramid, Unboxing Carbon, and *Grønn Materialguide* can be a way to get a better understanding of the possible material choices and their environmental impact.

2.2.6 Integration of LCA in the design process

To conduct a full LCA of a building a large quantity of information is needed. A building consists of different components, which again contain many different materials. A comprehensive data collection is a laborious task which can only be done in the late stage of the design process when a large quantity of information is available. Furthermore, scenarios for the lifespan of the building and its different building elements and materials need to be created. This and the end-of-life scenario are uncertain elements which can be accounted for in many ways. All of this makes LCA of buildings a complex and time-consuming process which is difficult to conduct without an extensive amount of knowledge about the building and its materials (Hollberg & Ruth, 2016).

This leads to the dilemma of the integration of LCA during the design process. In the early design stage, the most fundamental design decisions are made. Shape, number of storeys, orientation, and massing of the building have a great influence and are decided early in the development. In the next step, the materiality of the primary construction and the building envelope are defined generically. During all of these decisions considerations regarding embodied carbon in materials would help optimise the carbon footprint of the building, but the information needed to conduct a LCA is scarce, and assumptions are difficult to make. Figure 2.10 visualizes the dilemma by showing the relevance of the decisions and the uncertainties in the project with the cost impact there is in adjusting or changing decisions in the design process (Hollberg & Ruth, 2016).

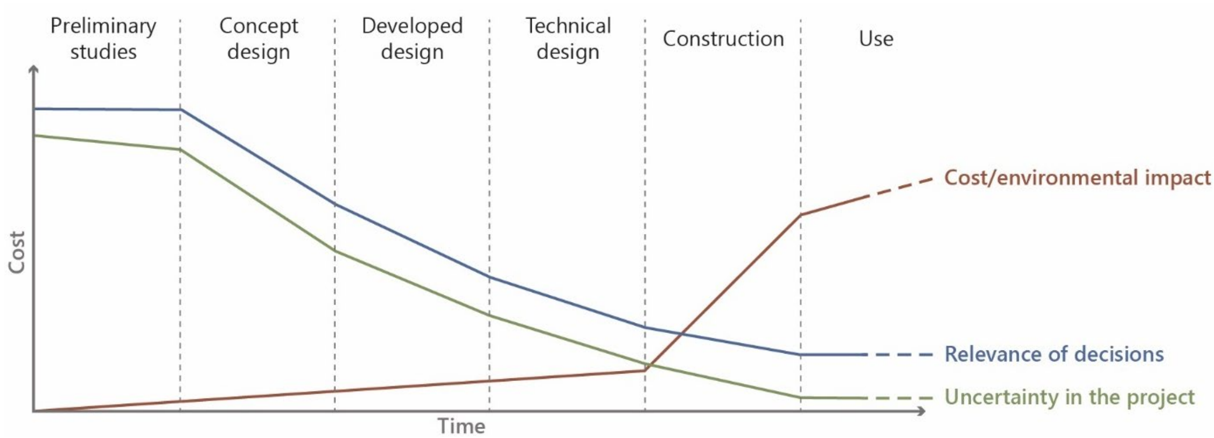


Figure 2.10: Planning dependencies between cost/environmental impact, relevance of decisions, and uncertainty in the project in the design and construction process.
Graphic created by author based on (Hollberg & Ruth, 2016)

Conventionally, LCA is, because of the previously described dilemma, mainly carried out exclusively for the purpose of certification at a late stage in the design process, when adjustments for lowering the embodied carbon are rarely possible and cost and planning intensive tasks. Figure 2.11 describes what an optimized implementation of LCA in the planning process could look like (Braune & Durán, 2018).

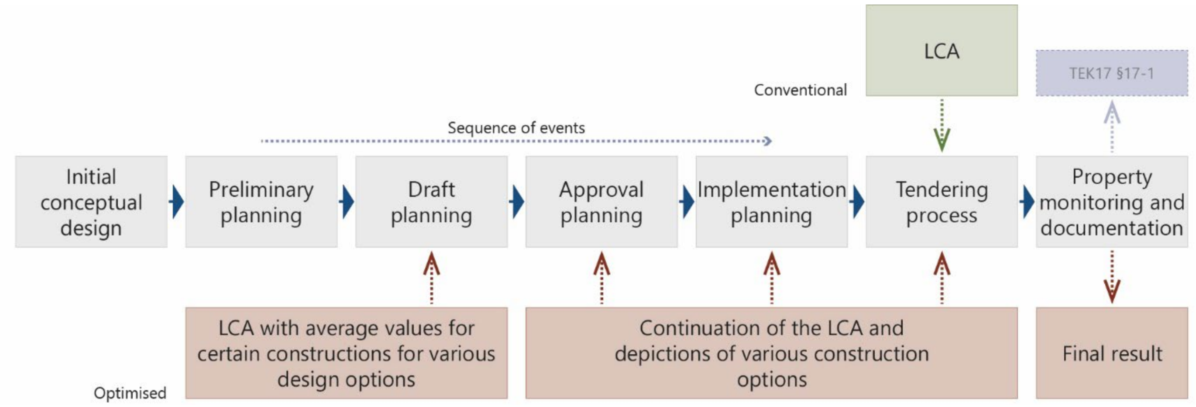


Figure 2.11: Conventional (green) vs. optimised (red) vs. TEK 17 (blue) application of implementing LCA in the planning process..
Graphic created by author based on (Braune & Durán, 2018)

LCA calculations are rarely conducted in the preliminary planning at present. However, if the main construction method is decided or discussed in this phase, it should be kept in mind that this predetermines in parts numerous materials and construction products. In the draft planning LCA with average values for certain construction for various design options has great potential to influence the carbon footprint. In this stage, individual components can be influenced. The environmental impact can be reduced by lowering the quantities of built-in materials and choosing renewable and recyclable materials when feasible. In the further design stages, the LCA should be continued, and various construction options should be tested out (Braune & Durán, 2018).

BREEAM-NOR offers a comprehensive framework for integrating various considerations that influence the rating of a building and outlines when they should be incorporated into the design process. Choices pertaining to materials (Mat) play a significant role in assessing embodied carbon and environmental performance. Figure 2.12 illustrates the timeline, using the Bygg21 framework, for setting material-related requirements during the design stages. Mat 01 involves the early-stage LCA calculation, which should be carried out in stage 3. The assessment is meant to recognise and encourage the use of construction materials with a low environmental impact over the full life cycle of the building. Mat 05 emphasizes durability and climate adaption to reduce the need for repair and replacement of materials, and should be considered in the second stage. Material efficiency and reuse, addressed in Mat 06, should be implemented from the second stage throughout all stages until handover and commissioning. Mat 07 covers aspects like the design for disassembly and adaptation, which should be addressed in stages 2 to 4 (Grønn Byggallianse, 2022).

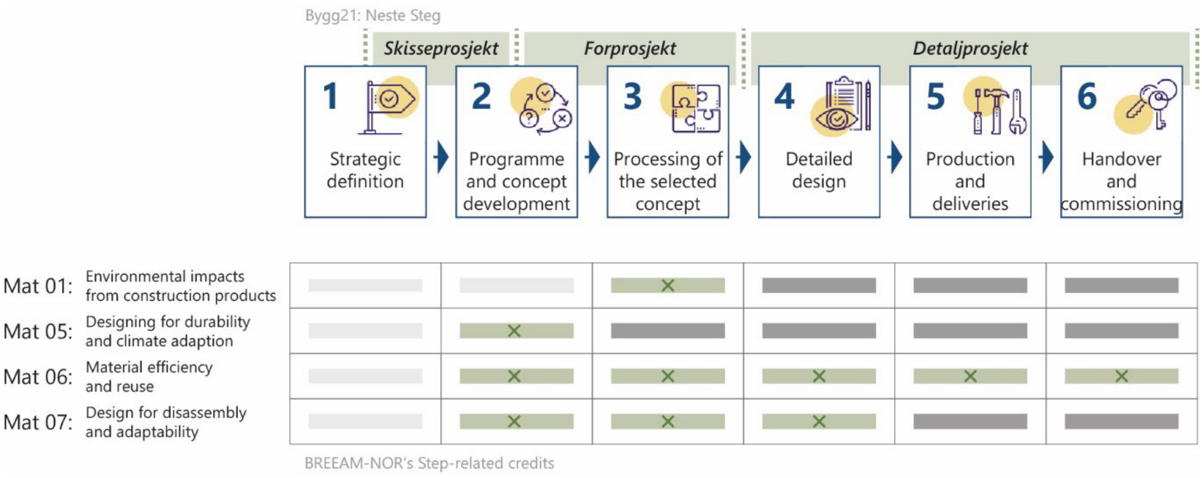


Figure 2.12: BREEAM-NOR's step-related requirements for material.
Graphic created by author based on (Bygg21, 2023; Grønn Byggallianse, 2022)

2.2.7 Embodied carbon's influence on architecture

Information regarding embodied carbon considerations influencing architectural designs in a holistic aspect is scares. Studies focus on segments of the bigger picture.

The embodied carbon in a building is influenced by the built-in material and their quantities. Optimizing the embodied carbon in a building is influenced largely by the material choices and the quantity in which they are implemented. It is not only the material itself which determines the environmental performance but also where it comes from, how it is built into the building, and what the possibilities are for it at the end-of-life stage. All these considerations have an impact on the design and expression of the building and the architect's work.

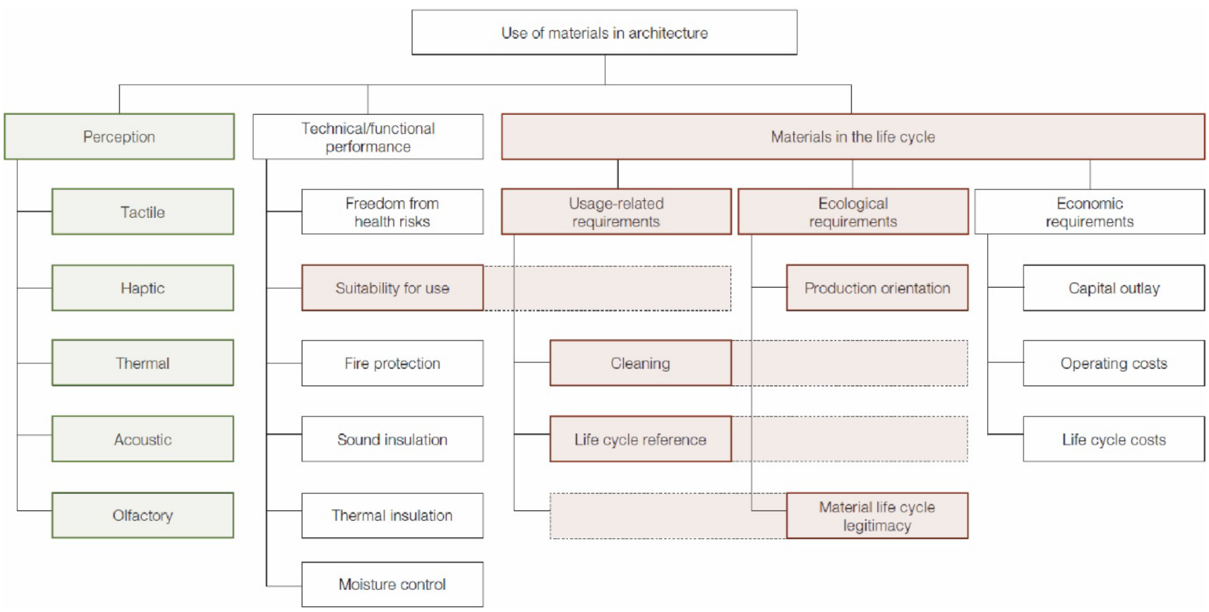


Figure 2.13: Aspects of material selection with perceptions highlighted in green and materials in the life cycle highlighted in red.
Graphic edited by author based on (Hegger, et al., 2012)

The materiality decision is determined by many aspects. Technical and functional performances influence whether a material is suited to fulfil the required demands put on it. Often one material alone cannot meet the standard, leading to multi-layered build-ups where the construction as a whole fulfils the requirements. In architecture, the perception of a material together with the favoured expression of the building influence the decision. This is an individual and subjective experience which is mainly observed via the building's surfaces. Figure 2.13 gives an overview of aspects influencing the material selection. Highlighted in green are the objective perceptions which are of large importance for the architecture. Highlighted in red are the factors which influence the materials' environmental performance, and which because of that embodied carbon in the building materials (Hegger, et al., 2012).

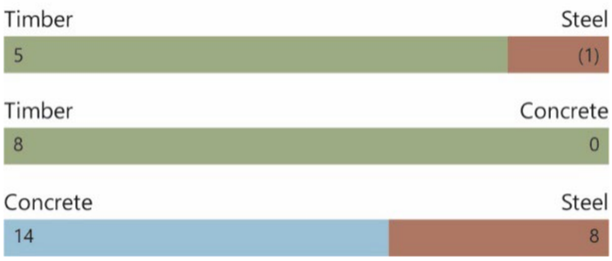


Figure 2.14: Comparison of timber, concrete and steel frames in terms of their GWP. The number represents the times one frame performed better than the one it was compared to.
Graphic created by author based on (Saade, et al., 2020)

Optimizing the load-bearing structure in relation to embodied carbon leads to a comparison of different systems and materiality. There are many studies comparing timber to concrete and steel constructions which have led to a common understanding that timber performs better than concrete and steel in an environmental assessment. Sadde, et al. (2020) confirm this perception. According to research timber framed buildings performs better than concrete or steel-framed buildings in almost all cases in terms of the GWP. The study looks at 11 papers with 36 buildings and concluded that in all comparisons between timber and concrete the timber building performed better (Figure 2.14). When comparing timber to steel there was one steel building which performed better than the timber counterpart. This one steel frame was built out of pre-engineered steel which has a high degree of material optimization and durability (Saade, et al., 2020). As the study is analysing other studies, the consideration and treatment of biogenic carbon in the assessments remain uncertain.

Despite the knowledge about the large quantity of embodied carbon in concrete, it is the most used construction material worldwide. In 2017 an average of one tonne concrete per person per year was consumed by humanity, which is more than any other construction material (Nazari & Sanjayan, 2017). Concrete by itself has a limited ability to withstand tensile forces, but in combination with reinforcement steel, it creates a composite material with the advantages of both materials. Freely formable, low cost and durability of concrete gets combined with high tensile strength of steel (Scheerer & Proske, 2008).

The concrete industry has recognised the need for products with lower embodied carbon and has issued the publication *NB37 Lavkarbonbetong* (NB37 Low-carbon-concrete) which classifies concrete into four different classes: Lavkarbon B, Lavkarbon A, Lavkarbon Pluss, and Lavkarbon Ekstrem (Norsk betongforening, 2019).

Basbagill, et al., (2012) present in their study different building components regarding their potential embodied impact allocation as a percentage of the total embodied emissions. They furthermore present the potential reduction when optimizing the material. This is meant to be a guideline for architects to develop an intuition on which decisions are most significant to the embodied carbon in a building. Figure 2.15 visualises the numbers presented in the study by Basbagill, et al., (2012).

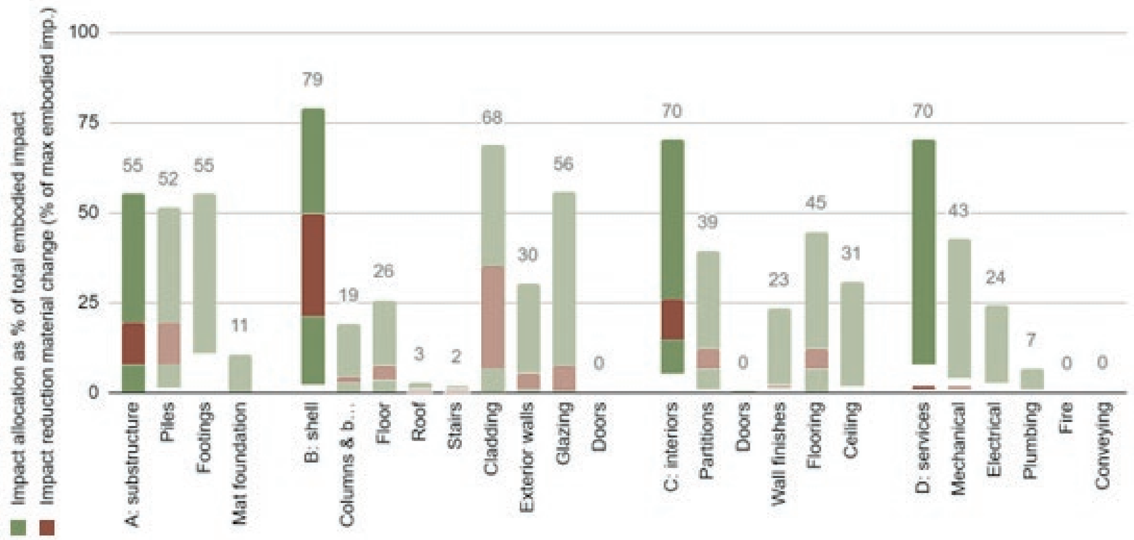


Figure 2.15: Impact allocation as % of the total embodied impact and impact reduction when the material is optimized as % of max embodied impact of different building elements.
Graphic created by author based on (Basbagill, et al., 2012)

Another study focuses on the impact environmental considerations have on the cost of a project. A study from the United States looks at 33 buildings with different LEED certifications and concludes that the additional cost varied between 1-5% compared to a conventional building on the same site (Yudelson, 2008).

2.3 Sample project Voldsløkka school

Voldsløkka school is a newly constructed secondary school located in Oslo, Norway and is promoted as Oslo's first plus energy with high environmental ambitions. The school is part of the ARV research project, investigating climate-positive circular communities in Europe. The design includes learning spaces for 810 students, a new culture hall, a dance hall, and a rehearsal space. The composition is made up of two buildings, the existing listed Heidenreich building (H-building) and the new plus-energy school building (S-building) (Figure 2.16). The H-building is an old cement factory which is converted into a cultural centre integrated into the surrounding community and public education activities. The new S-building facilitates classrooms and teaching areas as well as the auditorium (Lolli, et al., 2022).

Figure 2.16: Illustration of the Voldsløkka school project with the S-building on the right and the H-building on the left.
Illustration: Spinn Arkitekter AS & Kontur Arkitekter AS

The design process started out with the development of a Regulatory Plan, under the leadership of the Oslo City Planning and Building Agency. In this phase decisions regarding the treatment of the H-building, the demolition of the other buildings and the placement of the new S-building were taken. The width of the S-building was set to 22 meters, allowing for well-proportioned classrooms with daylight on the long side, and a central zone with studio rooms and open student workspaces. Furthermore, this allowed for the placement of the multi-purpose within the building footprint. The project went on to the pre-project phase where FutureBuilt definitions were discussed.

In the preliminary project (*Forprosjekt*) the architect offices Spinn Arkitekter AS and Kontur Arkitekter AS were appointed, together with various engineers and technical consultants. BIM software was used in this phase to navigate between the design and the requirements.

The detailed design phase had a duration of 100 weeks. In contrast to other design developments, the architects and the fire safety consultant were assigned to continue working on the project to ensure the overall environmental concept, quality, and characteristics were kept.

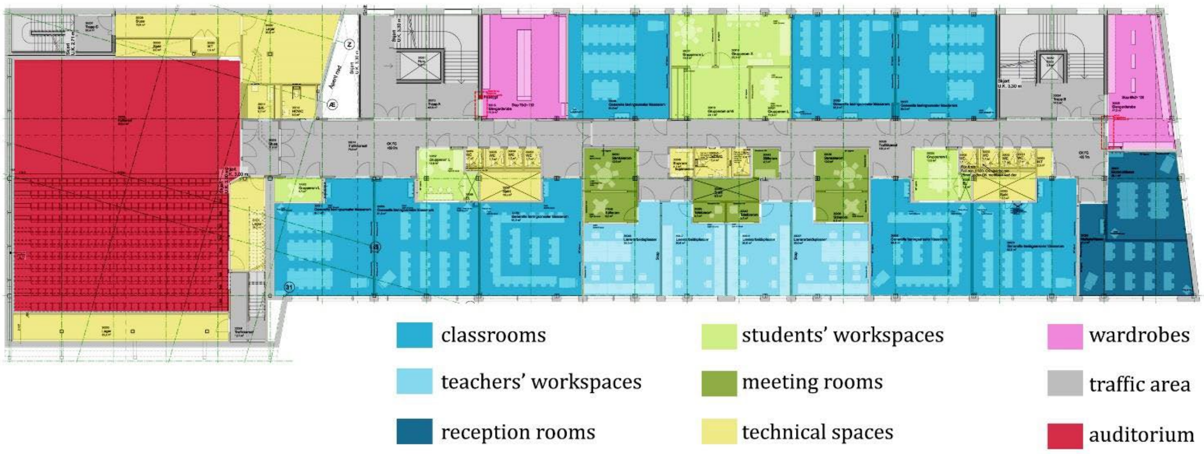


Figure 2.17: Regular floorplan of the S-building of Voldsløkka school with marking regarding the functions. (Lolli, et al., 2022)

The new S-building (Figure 2.17) has high environmental ambitions. It aims at being a plus-energy building and sets the benchmark for embodied emissions is a 50% reduction compared to local current practice. Two full LCA were performed by the subcontractor Norconsult, on for the early-phase design, an another one for the detailed design. The support system of the S-building is made of solid timber, steel, and concrete. The LCA was performed in alignment with NS 3720, used NS 3451 to organize the building elements, and estimated the service lifetime to be 60 years. Specific EPDs as well as generic emission intensities were used. A mix of supplier-specific, and standard values provided by the calculation software were used to determine material wastage, material lifetimes, transport distances, and end-of-life emissions (Lolli, et al., 2022).

The most impactful measures taken to reduce embodied emissions include the usage of "low carbon class A" concrete, 100% recycled reinforcement, large amounts of recycled steel in beams, increased usage of wooden materials for various building elements, and a lightweight roof structure made of solid timber (Lolli, et al., 2022).

The goal of lowering the embodied carbon of the building by at least 50% compared to reference values for standard Norwegian practice was reached (Lolli, et al., 2022).

3 Methodology

The main parts of this thesis are the interviews with five people working in architecture and engineering. The Interview methodology chapter presents the methodology for the interviews. Some findings or statements of the interviews are supplemented with considerations and calculations regarding embodied carbon in building materials. The methodology is presented in the Embodied carbon consideration methodology chapter. The general methodology for the development of this thesis is depicted in Figure 3.1.

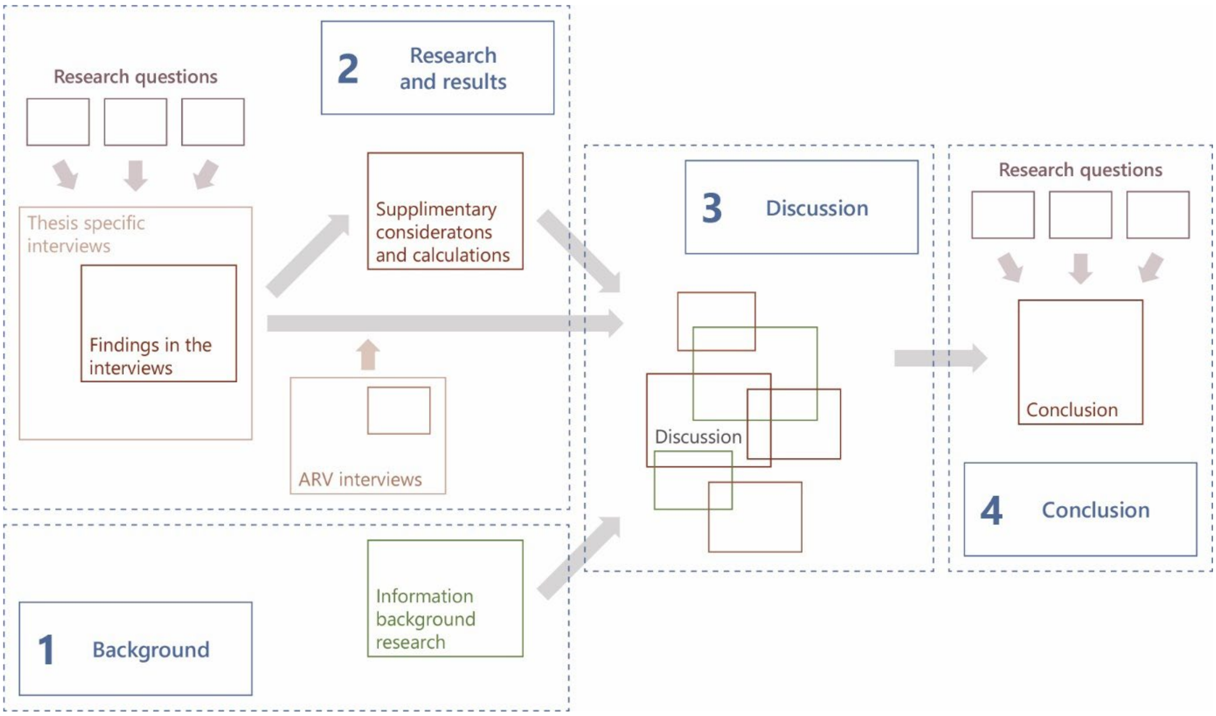


Figure 3.1: Illustration of the general methodology and workflow used to develop this study.

3.1 Interview methodology

The interviews are semi-structured interviews and follow the methodology described in this chapter.

3.1.1 Goal and scope

The goal of the interviews is to gain insight into the structure of the design process and how LCA is currently integrated and carried out in practice. These interviews will offer a subjective snapshot of the current situation from a sample of five interviewees.

The five interviewees were chosen to examine the topic from different sides and provide a brought view of the topic. A common objection to interview research is that there are too few subjects for the findings to be generalized. However, semi-structured interviews allow for a deep-dive into the subjects’ knowledge, in a way that a large sample would not allow.

3.1.2 Steps of the interview process

The interviews are structured according to the first five steps of interviewing proposed by Brinkmann & Kvale (2015):

1. Thematising: formulate research questions and theoretical clarification
2. Designing: planning the procedures and techniques
3. Interviewing: conduct the interviews
4. Transcribing: convert the conversation to a written mode amenable to closer analysis
5. Analysing: coding, structuring, and meaning interpretations

The theme of the interviews is given by the topic of the master's thesis. After some initial research and allocation of gaps in the available information, the framework for the interviews was set. The interviewees were preselected, and a focus was set on different backgrounds, offices, and work experience. The number of interviews was not set from the beginning but depended on the amount of information gathered in the interviews. In the end, five interviews were conducted.

The interviews were designed to be semi-structured following an interview guide (see Appendix 1). A second interview guide (see Appendix 2) was developed for the interview with the civil engineer, as some questions were too architecture specific in the first interview guide. The second guide is aiming to gather the same information but from the perspective of an engineer. Beforehand, the interviewees received the "Information Letter for Declaration of Consent" to inform the participants about the topic, and their rights and obtain consent to participation. Furthermore, a short questionnaire was included in order to retrieve basic information about the interviewee and adjust the questions asked according to the information gained from the questionnaire. To be able to interview people from different places in Norway, all interviews were conducted digitally on Teams. The interview was video recorded, and an automated transcript was created.

The interviews themself were conducted over a time of about five weeks due to the full schedules of the interviewees. Each interview lasted for about one hour during which the questions from the interview guide were asked and answered. The nature of a semi-structured interview allowed for some individual questions depending on where the interviewee was going with the answers to the questions. The interview language was English with the possibility of using, if necessary, Norwegian terms and explanations.

The transcript was done in the days after the interview and is based on the automatically generated transcript created by Teams. This transcript was compared to the video recording and adjusted where the automatic transcript did not match the audio of the video recording. The transcript is kept in an oral language, but filling sounds like "umm", "yeah", "ohh", filling words like, "so", "kind of", "like", and double words and stuttering were removed to make the transcript easier readable.

The base for the analysis of the interviews is the transcripts. In addition to the five interviews specifically conducted for this thesis four interviews from the ARV project about the Voldsløkka school project were included in the analysis.

3.1.3 Interviewees

Five people were interviewed specifically for this thesis. The interview code is used to link the collected statements with the original interview and by that give background to the scientific value of the statement in relation to the competencies of the interviewee.

Code	Background	Current work	Previous knowledge about LCA
#1	Architect	Design and planning of projects with a sustainable focus in all stages	Good knowledge from previous work and projects, Knowledge of circular economy and material health
#2	Architect	Design and planning in all stages, responsible for miljøoppfølgings-plan in the office	Limited knowledge from meetings with environmental consultants, Worked on a BREEAM project
#3	Architect	Early design stage (concept design)	Limited knowledge, no pre-knowledge from university
#4	Architect	Advising architects working on projects aiming for FutureBuilt certification	General interest in sustainability, FutureBuilt certification advisor
#5	Civil engineer	Research and teaching of LCA at university level	Started with indoor environment, energy and building physics, but branched towards LCA now and has now a broad knowledge about LCA

Table 3.1: Overview of the interviewees for the thesis-specific interviews.

In addition to these interviews, four interviews conducted in the ARV research project concerning the Voldsløkka school project were included in the analysis and screened for information or statements which would support the findings in the other interviews.

Code	Role in the project	Involvement in the project
D	Project developer from Oslobygg	Responsible for the project in the preliminary project. Obtained information from the person who worked with the project in the regulatory phase
E	Environmental advisor from Oslobygg	Worked on setting ambitions within the project early on. Was only involved before the preliminary design and detailed design.
M	Project managers from Oslobygg	Involved since the start of the preliminary project until the finish of the project.
A	Project architects from Spinn Arkitekter AS and Kontur Arkitekter AS	Involved since the preliminary project and throughout the tender process, together with the contractors and Oslobygg, up to the construction phase

Table 3.2: Overview of the interviewees included from the Voldsløkka school project.

3.1.4 Processing the interviews

Each transcript was read through, relevant statements were highlighted, and comments with summaries of the statements were added. In a further step, the statements and comments from the different interviews were structured and grouped in a spreadsheet (see Appendix 3). By structuring the findings of all the interviews into one spreadsheet it became possible to find similar and opposing statements.

The findings are grouped into three main categories; Architectural design process and involved parties, Integration of LCA into the design process, and Embodied carbon considerations and summarized in a table. Each finding is elaborated and specific statements or opinions from the interviewees are described.

The findings were screened for topics where further consideration would add value to the topic or clarify uncertainties. These considerations are presented in the chapter Embodied carbon considerations and LCA calculations and follow the methodology described in the following chapter.

3.2 Embodied carbon consideration methodology

The findings obtained from the interviews are complemented by detailed examinations of various considerations related to embodied carbon and LCA calculations. These additional considerations provide further insights and address controversies and uncertainty identified during the interviews.

3.2.1 Goal and scope

The primary objective of the considerations is to address the interview findings in a practical manner and by that gain further knowledge and insight. The extent of these considerations depends on the tools and knowledge available.

3.2.2 Tools

The simplified tools included in the considerations are the Construction Material Pyramid (CINARK - Centre for Industrialised Architecture, 2023), Unboxing Carbon - the Catalog (Henning Larsen, 2022), and *Grønn Materialguide* (Context AS & Grønn Byggallianse, 2021) as these are mentioned by the interviewees. For calculating the GHG emissions for transportation (A4) a simple calculation in Excel is conducted. All other calculations are conducted using Reduzer.

3.2.3 Calculation methods and system boundaries for LCAs

In this thesis embodied carbon is considered to be the GHG emissions of a building emitted by the production of materials used, the material-related transport, the emissions caused by the handling of the materials at the end of their life, and factors beyond the system boundary.

The calculation method NS 3720 and FutureBuilt Zero are used, with the detailed settings provided by Reduzer. If not mentioned differently, NS 3720 uses the pre-settings basic, without location and calculates the building with an ESL of 60 years. Biogenic carbon uptake is not taken into account in this scheme, while cement carbonation is included. There is no time horizon applied and technological development is not weight. FutureBuilt Zero system boundaries are set to meet the main criteria (*Hovodekriterium*). An ESL of 60 years is applied. The dynamic LCA includes biogenic carbon uptake and cement carbonation, as well as decreasing GWP impact with time and positive technological development over time.

TEK 17 §17-1 uses the NS 3720 calculation method and sets within this method specific system boundaries. These system boundaries are applied for calculations using TEK 17 as a method in this thesis.

Distance to the closest waste handling is set to 50km. For the transport distance of materials, the default simplified transportation distance included in Reduzer is used.

3.2.4 Automodel in Reduzer

The functionality in Reduzer called "Automodel" is used to create simplified options for the classroom tract of Voldsløkka school. Four alternatives (Opt. A - D) are created with different dimensions as depicted in Figure 3.2. For all options, the template data set *Skolebygg* (School building) provided by Reduzer is used for the quantities and material specification. Due to the lack of timber templates, this concrete and steel structure was chosen because of the same function of the building. For a better understanding of the template refer to Appendix 4.

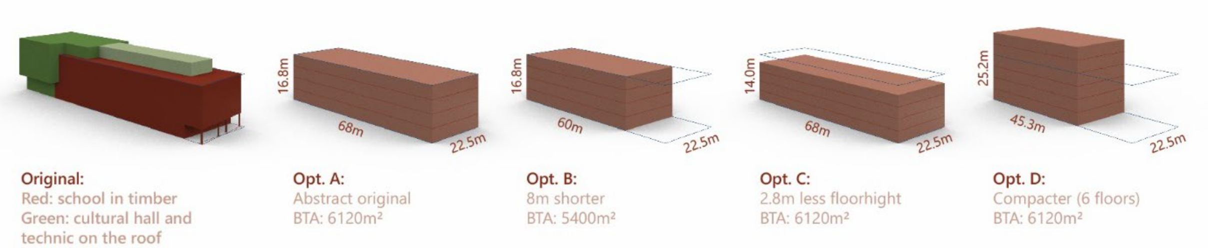


Figure 3.2: Illustration of the four Options (Opt. A - D) for the classroom tract of Voldsløkka school.

Option A is as close to the original as possible with the limited input options provided by Reduzer's Automodel. It has a BTA of 6120 m^2 and consists of four stories with a floor-to-floor hight of 4.2m. Option B is 8m shorter and has due to that only a BTA of 5400 m^2. Option C has the same footprint and BTA as option A but due to a reduced floor-to-floor hight (reduction by 0.7 m from 4.2 m to 3.5 m) less volume. Option D has the same BTA and floor-to-floor hight as option A but is compacter as its length is shortened by 1/3 and to compensate for that two floors are added which leads to the same BTA and volume but in a compacter shape.

4 Results

This chapter presents the findings of the interviews, considerations about embodied carbon and LCA calculation. The latter two are developed based on the findings, statements and uncertainties of the interviews.

4.1 Findings from the interviews

The findings from the thesis-specific interviews are structured into seven topics (A to F), presented in Table 4.1, Table 4.2, and Table 4.3. Topics A to C are presented in more detail in the chapter Architectural design process and involved parties, Topic D and E in the chapter Integration of LCA into the design process, and Topics F and G in the chapter Embodied carbon considerations and influences. Furthermore, similar findings from the Voldsløkka school interviews are added to the findings from the thesis-specific interviews.

Architectural design process and involved parties	**Topic A**	**Structure of the design process**
	Finding A1	The architects and engineers are not using a clear uniform structure in the design process and the terminology is inconsistent.
	Topic B	**Involvement of the AEC and clients**
	Finding B1	Clients show an interest in more sustainable buildings and low-carbon materials. They see value in the investment and initiate buildings with environmental goals and benchmarks.
	Finding B2	Clients have a large influence on the projects and with that the environmental impact. They set the design brief, specific requirements, and the financial framework for projects.
	Finding B3	Engineers and consultants are involved according to the needs of the project. In traditional project structures, there is a tendency not to involve them early and only if necessary.
	Finding B4	Engineers and consultants get earlier involved in design projects with environmental goals. In projects aiming for high standards regarding environmental impact, the involvement of an environmental consultant is essential right from the outset of the project.
	Topic C	**Usage of BIM in the design process**
	Finding C1	All three practising architects use 3D drawing tools for their work. BIM is used in some stages and for more specific tasks.
	Finding C2	There is some scepticism towards using BIM in the early design phase because of the lack of information and the difficulties of creating variants.

Table 4.1: Summary of the main findings from the interviews regarding the architectural design process and the involved parties.

Integration of LCA into the design process	Topic D	LCA calculations during the design process
	Finding D1	It is difficult to do meaningful LCA calculations in the early design phase and account for the uncertainties and lack of knowledge.
	Finding D2	LCA calculations in the early design phase are general and mainly done to get a better understanding of the larger picture.
	Topic E	**Choices during the design process**
	Finding E1	Architects integrate considerations regarding the materiality of a building from the beginning of a design process as this has a large influence on the project.
	Finding E2	The primary aspect to prioritize and determine in terms of materials is the building structure and load-bearing system.
	Finding E3	The selection of most other materials can be postponed until a later stage, unless specific preferences or concerns require earlier attention.

Table 4.2: Summary of the main findings from the interviews regarding the integration of LCA into the design process.

Embodied carbon considerations and influence	Topic F	Material choices
	Finding F1	When choosing materials, architects not only focus on low-carbon materials, but also on factors like recycling, reuse, and longevity.
	Finding F2	Timber is mentioned as a low-carbon building material which would contribute to reducing embodied carbon and would be a favourable material choice compared to others.
	Finding F3	Concrete and steel are mentioned as materials sometimes favoured by engineers, consultants and clients, as they are well known and used on a large scale.
	Finding F4	Bricks and their embodied carbon is viewed differently by the interviewee. There are three standpoints. 1. The longevity makes up for the large emissions. 2. the longevity does not justify the large emissions. 3. Do only use brick if necessary and be cautious about choosing a material with low embodied emission or reuse.
	Topic G	**Inputs on how to lower embodied carbon**
	Finding G1	Try to reduce the quantity of used material. This can for example be done by reducing the built square meters or reusing existing building mass.
	Finding G2	Try to limit the construction of basement and foundation.
	Finding G3	Choose materials not only according to their embodied carbon from production, but also encounter other characteristics that affect the entire lifecycles of materials and buildings.

Table 4.3: Summary of the main findings from the interviews regarding embodied carbon considerations and influence.

4.1.1 Architectural design process and involved parties

Finding A1:	The architects and engineers are not using a clear uniform structure in the design process and the terminology is inconsistent.

In the thesis-specific interviews, Bygg21 seems to be the best-known structure for the design process. Nevertheless, it was not possible to define and use clear terms for the design phases throughout the interviews. The terms *Skisseprosjekt, Forprosjekt* and *Detaljprosjekt* were sometimes mentioned but mostly the phrase "early design" was used to describe the *Skisseprosjekt* and/or *Forprosjekt*.

In the interview transcripts for Voldsløkka school, no consistent translation of the terms to describe the different design phases was used. It can be summarized that the interviewees talked about the *Reguleringsfase* (regulatory phase), the *Tidligfase* (early phase), *Forprosjekt* (preliminary design or project / pre-project / design or project development phase), and *Detaljprosjekt* (detailed design). *Skisseprosjekt* was not mentioned in the Voldsløkka school interviews. This is most likely due to the structure of the project where after the *Reguleringsfase* the project went over into the *Forprosjektfase*.

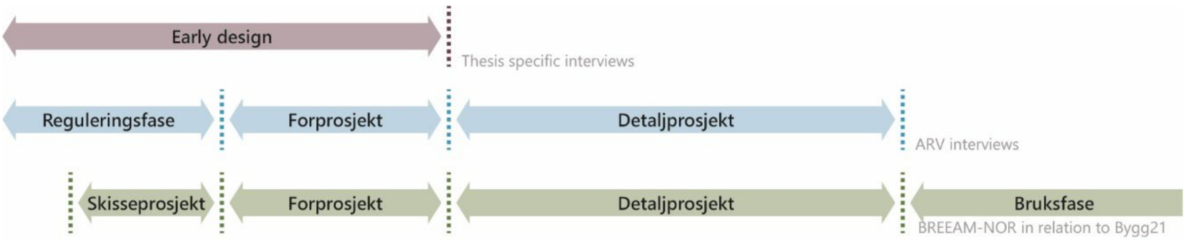


Figure 4.1: The terminologies used to describe the different design phases used in the interviews compared to the BREEAM-NOR in relation to Bygg21 terminology.

Finding B1:	Clients show an interest in more sustainable buildings and low-carbon materials. They see value in the investment and initiate buildings with environmental goals and benchmarks.
Finding B2:	Clients have a large influence on the projects and with that the environmental impact. They set the design brief, specific requirements, and the financial framework for projects.

All architects have experience with some clients showing an interest in more sustainable buildings and setting environmental requirements. It is also mentioned in the interviews that goals and benchmarks help to get all the involved parties to focus on one common vision for the project. Clients are perceived as crucial decision-makers in the design process, influencing some aspects of a project before the architects get involved. These decisions include more general topics like the design brief and space descriptions, demolishment or refurbishment, the placement of a building on the plot, as well as more detailed decisions on specific concepts and materials. There was a focus on the influence clients take on the material choice. One mentioned reason for this is the financial impact the materiality has on a building. Interviewee #1 mentioned that some clients do not emphasize the topic of sustainability but propose to find out where the pressure points are and educate people about them.

The Voldsløkka school project is an example where the client set ambitious goals regarding the environmental impact of the school from the beginning. The client decided on demolishment and refurbishment, the setting of the building volumes on the plot and the materiality of the building, and left little the architects little room for change or adaptation.

Finding B3:	Engineers and consultants are involved according to the needs of the project. In traditional project structures, there is a tendency not to involve them early and only if necessary.
Finding B4:	Engineers and consultants get earlier involved in design projects with environmental goals. In projects aiming for high standards regarding environmental impact, the involvement of an environmental consultant is essential right from the outset of the project.

According to the interviews, the involvement of the engineers and consultants depends on the project. Smaller and more conventional projects tend to start the interdisciplinary process later. Interviewee #2 sees the problem in the financial risk for the client of involving engineers and consultants earlier, but points out, that if the project goes into the next stage the base is much better. Interviewee #4 sees the problem in the collaborative way architects and engineers work together and that often architects lead the development and engineers add their expertise later. This leads to suboptimal solutions because the early design decisions taken by the architect might not consider and integrate the technical aspects in the most optimized way.

The interviewees also mentioned that they see a tendency of involving engineers and consultants earlier in ambitious or large projects. Furthermore, the interdisciplinary work in those projects is more intense.

The Voldsløkka school project has high ambitions regarding environmental impacts. From the interviews, it can be concluded that the technical aspects were considered quite early in the project. During the *Forprosjekt* the interdisciplinary project team was working in the same location. This improved the coordination and workflow of the planning.

Finding C1:	All three practising architects use 3D drawing tools for their work. BIM is used in some stages and for more specific tasks.
Finding C2:	There is some scepticism towards using BIM in the early design phase because of the lack of information and the difficulties of creating variants.

All three practising architects use in one way or another 3D drawing tools in their daily work. But BIM is not the main tool. Interviewees #1 and #3 say that they struggle with the limited flexibility of detailed BIM models and because of that do not use it to develop different variants and options. Interviewee #2 sees the limitations occurring due to BIM but thinks that being aware of these limitations helps to enable architects to apply BIM in early phases.

There is some scepticism towards BIM in the early phase by almost all interviewees. The problem they see, and experience is the large amount of information needed to create BIM models and the scarcity of information in the early design phases. Similar to the early engagement of engineers, investing in a detailed BIM model poses a financial risk for the client, especially when there is a significant possibility of the project not progressing further. Additionally, interviewee #3 mentions that clients want quick sketches and answers in the early design.

In the Voldsløkka school project, BIM was implemented in the *Forprosjekt* to coordinate information and requirements.

4.1.2 Integration of LCA into the design process

Finding D1:	It is difficult to do meaningful LCA calculations in the early design phase and account for the uncertainties and lack of knowledge.
Finding D2:	LCA calculations in the early design phase are general and mainly done to get a better understanding of the larger picture.

During the interviews, there was no intended focus on early design LCA, but all interviewees focused mainly on early calculations. It got pointed out that early design calculations are rather unprecise and need to account for the uncertainties and lack of knowledge at that stage. In the early phase, it is sensitive to get a better understanding of the potential embodied carbon of the building. Calculations should rather be comparisons than in-depth calculations. Furthermore, it is suggested that using generic and conservative data at the initial stages is preferable to avoid overly optimistic and unattainable calculations upon which decisions are made. Hereby the used tools are of importance. The tool should be adjusted according to the design stage and the focus of the calculation. Interviewee #1 mentions that it is important to pre-sort the choices and divide them into different systems before starting with software analyses. Interviewee #5 mentions the CINARK Construction Material Pyramid as a potentially helpful tool in the early stage. Other useful tools for the early stage which got mentioned during the different interviews are the Unboxing Carbon Catalog from Henning Larsen and the *Grønn Materialguide* from *Grønn Byggallianse* (Green Material Guide from Green Building Council).

Finding E1:	Architects integrate considerations regarding the materiality of a building from the beginning of a design process as this has a large influence on the project.
Finding E2:	The primary aspect to prioritize and determine in terms of materials is the building structure and load-bearing system.
Finding E3:	The selection of most other materials can be postponed until a later stage, unless specific preferences or concerns require earlier attention.

While interviewees #4 and #5 emphasized the importance of considering materials from the initial design phase, this is confirmed by all practising architects that the materiality of a building is taken into account from the beginning of a project. The first thing which is and should be considered is the load-bearing system. This is determined at an early stage in the design process and has a large influence on the building's shape and concept. Interviewee #3 mentions an example from the office. Initially in this project, a structure made entirely of timber was planned in order to use a sustainable and renewable material. Early on the architects struggled with the horizontal loads and the quantities of cross bracing required in a timber building. In collaboration with the structural engineer, an alternative material proposal was developed. While the main part of the building remained to be timber, the shafts' materiality changed to reinforced concrete with the ability to improve the cross-bracing of the building. An LCA comparison for the two options was carried out by an external expert. The result of the comparison was used to lead the client's decision towards the optimized structure with a combination of timber and concrete.

The interviewees expressed the belief that apart from the load-bearing system most other materials choices can be postponed to a later stage. Nevertheless, any specific preferences should be addressed and integrated early into the project.

Findings in the Voldsløkka school interviews comply with the three findings on this topic. The materiality was discussed early in the design process of the Voldsløkka school project. The choice of the building system went through a similar process as described by interviewee #3. The ambition was to use as much timber as possible. The large spans of some of the spaces made the use of only timber unreasonable. A concept was developed where the building parts containing the classrooms and teaching areas were planned with a load-bearing system out of timber, while the larger public spaces like the auditorium had a change in materiality to steel and reinforced concrete. The quality of the finishing surface was defined quite early in the design, which is according to the architects of the Voldsløkka school project the reason why the final project has so high quality materials.

4.1.3 Embodied carbon considerations and influences

Finding F1:	When choosing materials, architects not only focus on low-carbon materials, but also on factors like recycling, reuse, and longevity.

The answers of the interviewees show a significant overlap in the aspects mentioned regarding their focus when selecting materials and potential strategies to reduce embodied carbon. The interviewees largely focused on factors like longevity, reusability, and recyclability when asked about the influencing factors of material choices. More obvious influences like optic, haptic, acoustics, transport distance, or personal preferences did not get mentioned. Only interviewee #5 mentioned that architects mainly focus on aesthetics and surface materiality.

Finding F2:	Timber is mentioned as a low-carbon building material which would contribute to reducing embodied carbon and would be a favourable material choice compared to others.
Finding F3:	Concrete and steel are mentioned as materials sometimes favoured by engineers, consultants and clients, as they are well known and used on a large scale.
Finding F4:	Bricks and their embodied carbon is viewed differently by the interviewee. There are three standpoints. 1. The longevity makes up for the large emissions. 2. the longevity does not justify the large emissions. 3. Do only use brick if necessary and be cautious about choosing a material with low embodied emission or reuse.

During the interviews timber, concrete and steel, and brick were discussed in more depth.

Timber was mentioned as a low-carbon building material which should be used in larger quantities as a building material. Interviewee #3 talked about a project where timber was the preferred construction material, but because of the stiffness of the building a combination of timber and reinforced concrete was developed to utilize the advantages of both materials. Interviewee #5 points out that timber is, considering the embodied carbon, a preferable material, but nevertheless, the sufficiency of quantities is still an important topic to consider.

In the Voldsløkka school project timber was the preferred material, but in order to handle the wide spans of the auditorium and larger public spaces not all of the building was feasible to build with timber. While the classroom and teaching area is executed with timber as the main load-bearing system and reinforced concrete stairway shafts, the larger spans are constructed in concrete and steel. The difference in materiality is integrated into the concept and marks the different functions of the areas.

Concrete and steel are mentioned as materials sometimes favoured by engineers, consultants and clients, as they are well known and used on a large scale. Clients and economic experts have more experience with concrete and steel and may perceive the use of less-known materials like timber as a potential risk. Similar statements are made about structural engineers who often have more experience in calculating and designing concrete and steel structures than timber structures.

Bricks were discussed controversially in the interviews. There were mainly three opinions about this material. Interviewee #1 mentions that they steer towards bricks which are produced with less CO_2-intense energy sources like biogas or upcycled bricks. Both of those measures would lead to materials with lower embodied carbon. Interviewee #2 considered brick to be a "good" material due to its longevity and despite its large embodied carbon. Interviewee #5 argues that the potential long lifespan of bricks is not a valid argument for the large embodied carbon as it is not possible to predict how materials are reused, recycled, or upcycled in the future. Interviewee #4 mentions bricks together with concrete and steel as heavy materials with large embodied carbon which should be used with care and limitations.

Finding G1:	Try to reduce the quantity of used material. This can for example be done by reducing the built square meters or reusing existing building mass.
Finding G2:	Try to limit the construction of basement and foundation.
Finding G3:	Choose materials not only according to their embodied carbon from production, but also encounter other characteristics that affect the entire lifecycles of materials and buildings.

All architects propose reducing the quantity of material used as a means to decrease embodied carbon and mention different measures to achieve a reduction. Compact buildings with smaller wall-to-floor ratios reduce the overall consumption of material. Another proposed measure is reducing the built square meters. Keeping and extending the existing building mass enable the reduction of new material.

Another potential the interviewed architects see is the limitation of constructed basements and foundations. Not only do basements require huge land movements but also the conventional material for underground construction is concrete combined with plastic in order to get the building water and moister tight.

The interviewees mention the importance of selecting materials not only based on their low embodied carbon but also on their longevity, ensuring they require minimal replacement or maintenance over time. Furthermore, the details should allow for easy maintenance and enable future disassembly. Additionally, reused or recycled materials are preferable. Interviewee #5 points out that the effort in designing and building those details needs to be in relation to the uncertainty of disassembly, reuse and recycling actually happening in the future. Interviewee #5 points out that the design and construction efforts should be balanced with the uncertainty of disassembly, reuse, and recycling practices in the future.

4.2 Embodied carbon considerations and LCA calculations

In this chapter, the findings from the interviews are examined with assumptions, considerations and calculations. This is meant to shine a brighter light on certain aspects of embodied carbon in building materials and provide more relatable insight into the topic. Details regarding the calculations can be found in Appendix 5 to Appendix 11.

4.2.1 Consultation of simplified tools

Construction Material Pyramid and functional units

The Construction Material Pyramid can not only be used to compare different materials but also to emphasize the importance of using the right functional unit. Figure 4.2 compares three sorting systems focusing on foam glass, stone wool, and glass wool. These three materials belong to the category of mineral / natural stone materials and are common insulation materials.

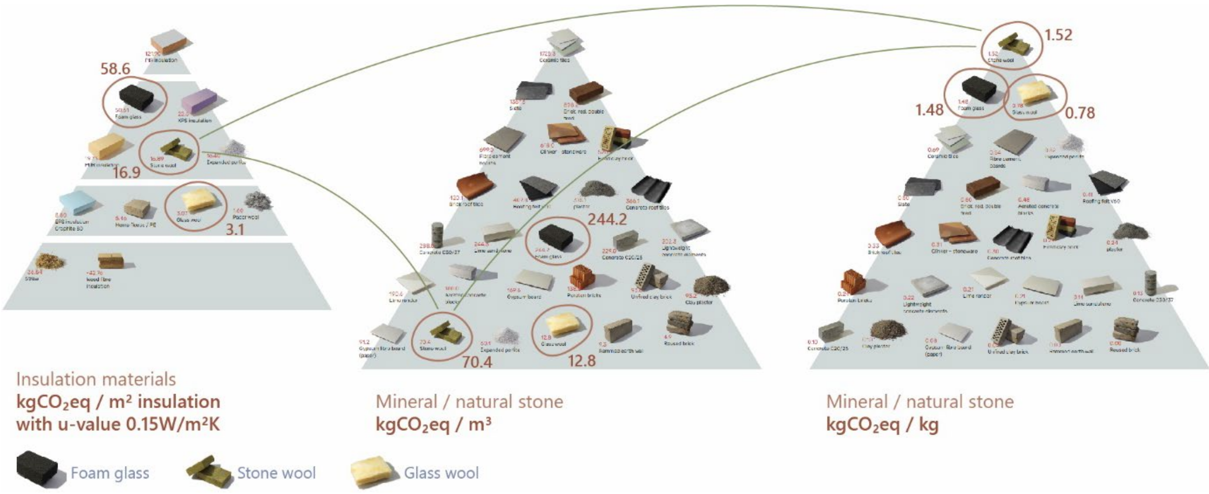


Figure 4.2: The Construction Material Pyramid comparing three different sorting systems of the pyramid to point out the importance of functional units. Left: $kgCO_{2eq}/m^2$ insulation with u-value 0.15 W/m^2K. Middle: $kgCO_{2eq}/m^3$. Right: $kgCO_{2eq}/kg$.

The pyramid to the left shows insulation materials sorted according to the functional unit $kgCO_{2eq}/m^2$ insulation with u-value 0.15 W/m^2K. Meaning, the thickness of all the insulation material is calculated to achieve a u-value of 0.15W/m^2K. The pyramid in the middle displays mineral / natural stone materials sorted according to the functional unite $kgCO_{2eq}/m^3$ while the right pyramid presents a sorting according to the functional unite $kgCO_{2eq}/kg$. The comparison of those three pyramids emphasizes the variability in material ratings based on the functional unit. Sorting the pyramid according to the functional unit $kgCO_{2eq}/m^2$ insulation with u-value 0.15 W/m^2K holds the most significance for architects as this allows the comparison of insulation materials which achieve the same function in a building.

Unboxing Carbon Catalog and transport distance

The Unboxing Carbon Catalog gives a good overview of different façade materials, especially brick. Brick is, with a density of about 1450 to 1800 kg/m^3, a relatively heavy material. The GHG emissions for transportation (A4) can be calculated by the mass of material transported multiplied by the emission intensity per tonne and km. This leads to larger GHG emissions for heavy materials. Taking seven of the lower-emitting brick products presented in the Unboxing Carbon Catalog (see Figure 4.3) and adding the GHG emissions from the transportation distance (A4) influences the environmental performance of the brick.

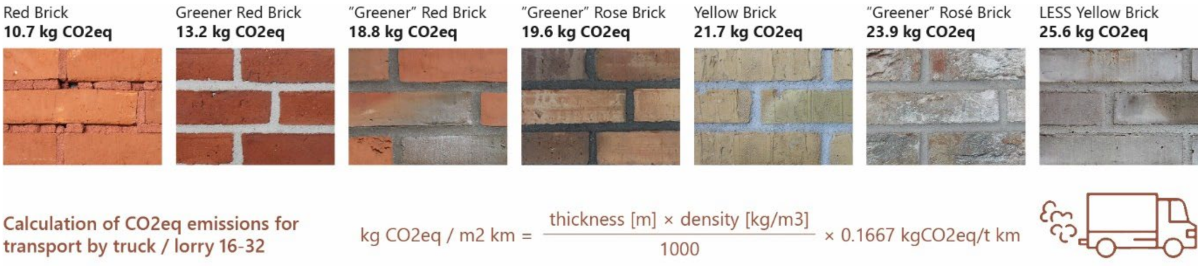


Figure 4.3: Bricks from the Unboxing Carbon Catalog used to analyse the effect of including the transport distance (A4) to the emissions per square meter.

Figure 4.4 illustrates the effect of adding stage A4 to the scope of the Unboxing Carbon Catalog. Lighter bricks cause slightly less GHG emissions in transport compared to heavier bricks. More important is the distance a product is transported. Locally produced material might perform better when including stages A1-A4 into the considerations.

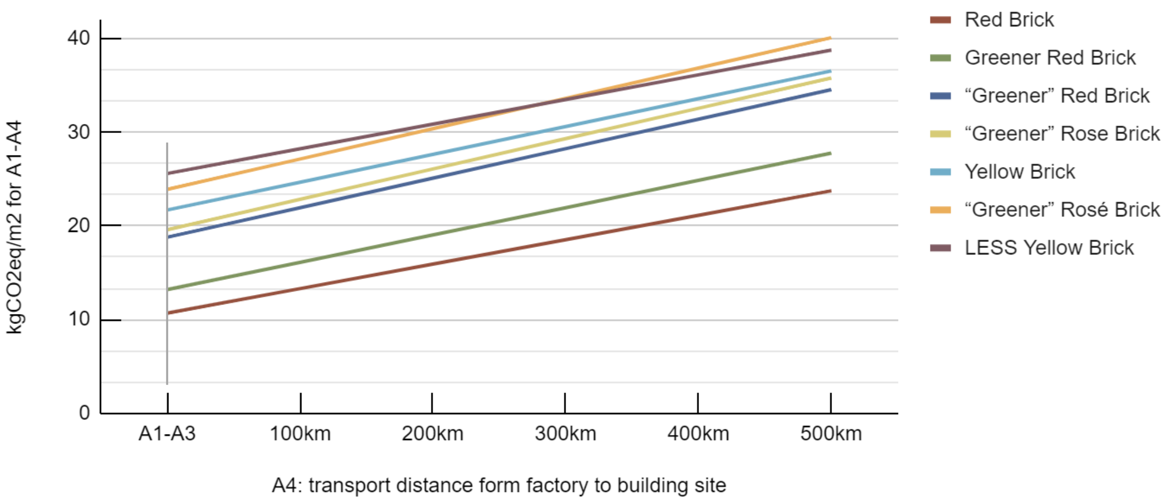


Figure 4.4: Comparison of the GWP of different bricks from the Unboxing Carbon Catalog (A1-A3) when the GHG emissions for transport (A4) are included.

Construction Material Pyramid and *Grønn Materialguide* and biogenic carbon

The Construction Material Pyramid includes biogenic carbon for its evaluation of the building materials.

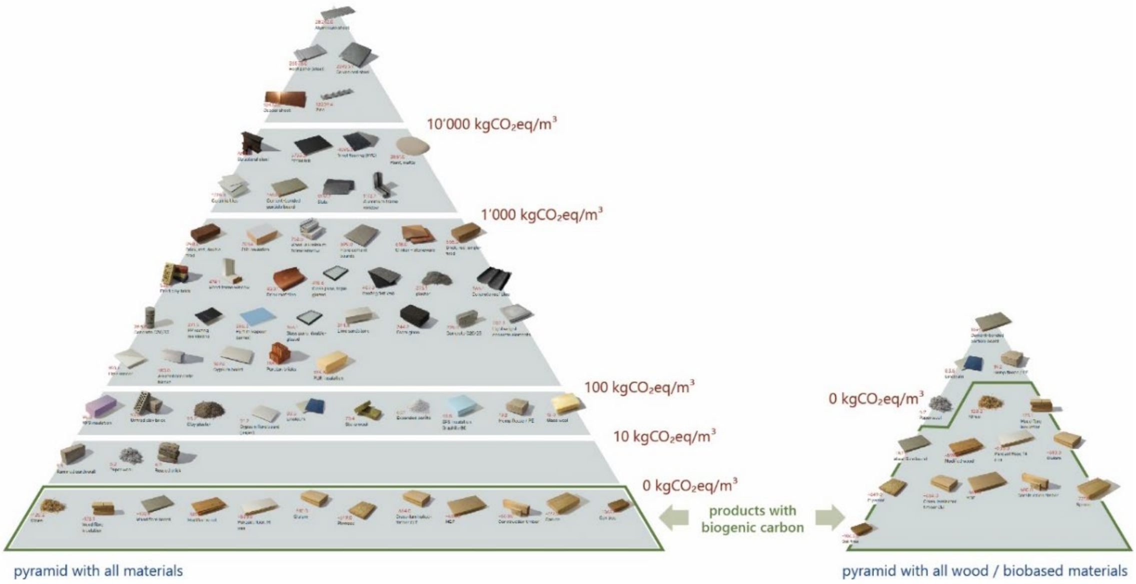


Figure 4.5: The Construction Material Pyramid with all materials (left) compared to the pyramid with wood / bio-based materials (right) regarding the positioning of the wood / bio-based materials.

When assessing all the products listed in the Construction Material Pyramid according to their GWP per cubic meter ($kgCO_{2eq}/m^3$) products mainly consisting of wood or bio-based are at the base of the pyramid (see Figure 4.5). These materials have negative embodied carbon as the carbon uptake during their growth, which leads to a negative number in the GWP, is included in A1-A3. It is important to keep in mind, calculations of embodied carbon in buildings do not necessarily include the biogenic carbon in their calculations.

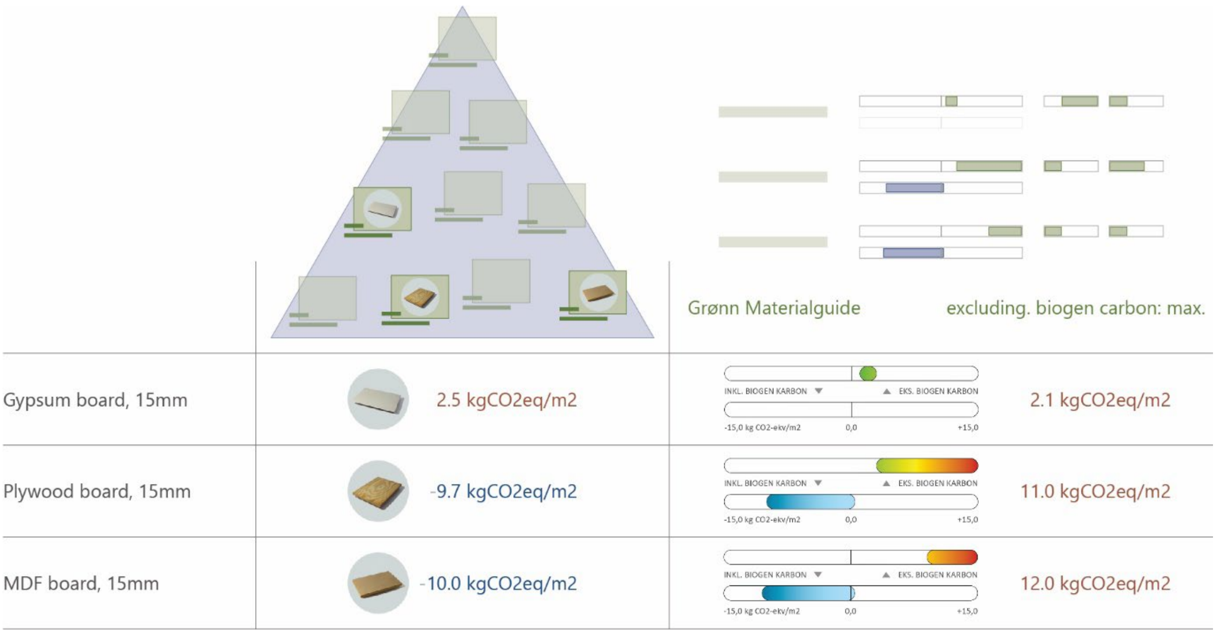


Figure 4.6: Illustration of the difference between the Construction Material Pyramid and the Grønn Materialguide regarding biogenic carbon by depicting the building boards out of gypsum, plywood, and MDF.

The *Grønn Materialguide* solves the issue of including or excluding the biogenic carbon in a more user-flexible way. The documentation includes values for both options, providing transparency and clear visibility of the differences. Figure 4.6 illustrates the difference between the Construction Material Pyramid and the *Grønn Materialguide* by looking at the building boards (*bygningsplater*) gypsum (*gipsplater*), plywood (*kryssfiner*), and MDF (*MDF plater*). Consulting the *Grønn Materialguide* for simple guidance illustrates well what influence the biogenic carbon has on the GHG emissions of a material.

4.2.2 Biogenic carbon

NS 3720 and FutureBuilt Zero calculating biogenic carbon

As previously demonstrated, simplified tools incorporate biogenic carbon in various ways. When conducting an LCA using the calculation method from NS 3720 in Reduzer, biogenic carbon is not taken into account. FutureBuilt Zero, in contrast, includes biogenic carbon as a carbon uptake by a tree growing replacing the tree which is now storing the carbon in the building material. Consequently, this results in a negative GWP in stage B1 when calculating with FutureBuilt Zero. The biogenic carbon is released later in the lifetime of the building, when the material is waste handled. Thus, the net effect is only the temporary storage of the biogenic carbon.

To visualize this, a comparison of two cantilevered slabs is demonstrated below. The CLT slab uses the build-up from the classroom tract of Voldsløkka school. For the comparison, the load-bearing system is exchanged for a concrete hollow-core slab. Both systems are prefabricated elements which can be supplemented with the same floor build-up. The build-ups are depicted in Figure 4.7.

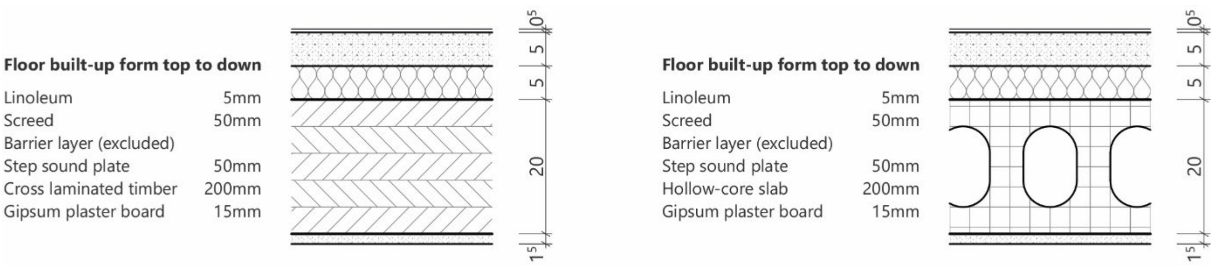
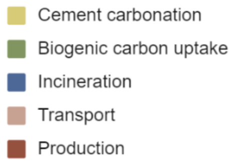


Figure 4.7: Floor build-ups for comparison. Left: CLT slab with floor build-up. Right: Concrete hollow-core slab with floor build-up.

The comparison presented in Figure 4.8 shows in which life cycle stage biogenic carbon is accounted for, when performing a holistic LCA with NS 3720 and FutureBuilt Zero. When assessing the components using NS 3720, they get similar GWP values. Both components have lower GWP values when applying the dynamic LCA calculation method considered in FutureBuilt Zero. Due to the larger quantity of bio-based material in the CLT slab, its GWP is 8% lower in comparison to the alternative concrete hollow-core slab.

Floor build-ups and calculation method	GWP/m^2
CLT slab with floor build-up (NS 3720)	112 kg CO_{2eq}
CLT slab with floor build-up (FutureBuilt)	80 kg CO_{2eq}
Concrete hollow-core slab with floor build-up (NS 3720)	113 kg CO_{2eq}
Concrete hollow-core slab with floor build-up (FutureBuilt)	97 kg CO_{2eq}

Table 4.4: The total GWP/m^2 for the floor build-ups calculated with NS 3720 and FutureBuilt Zero



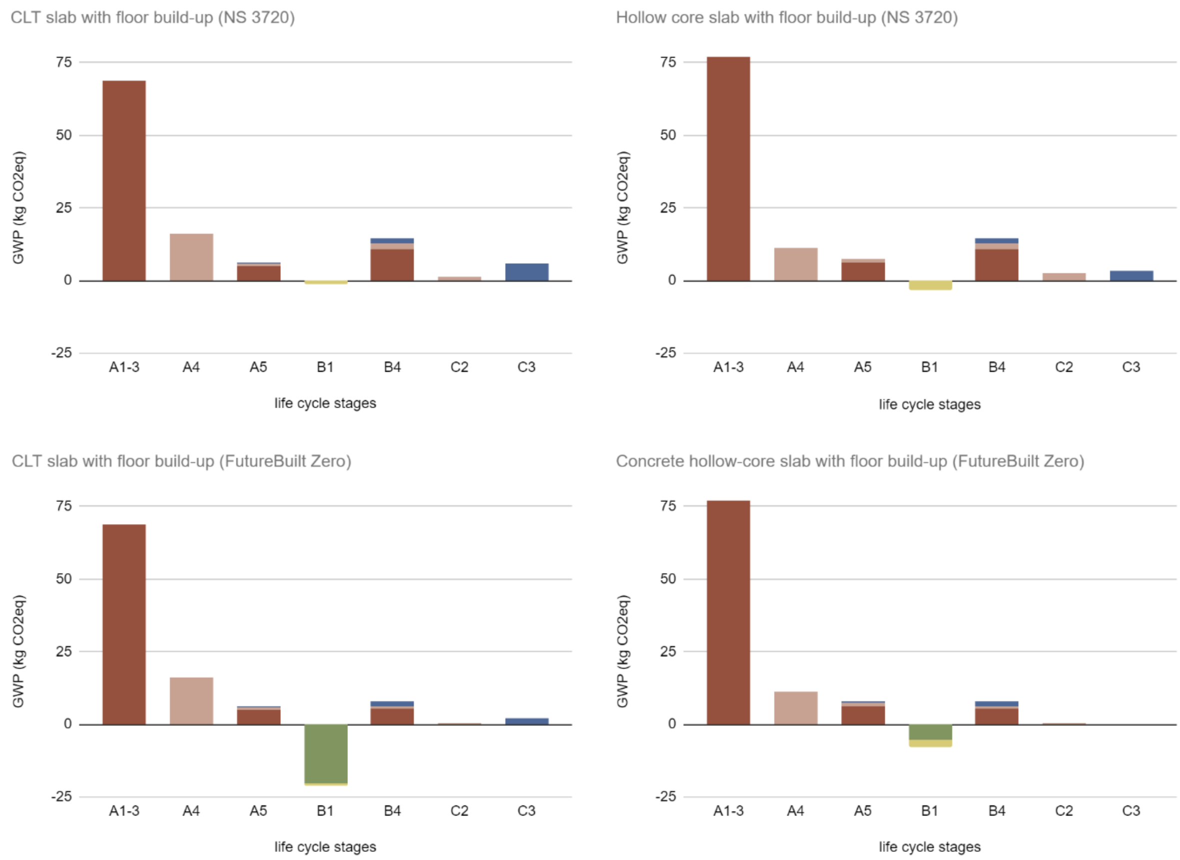


Figure 4.8: Comparison of the CLT slab (left) to the concrete hollow-core slab (right) regarding their GWP when calculating with the method by NS 3720 (top) and FutureBuilt Zero (bottom).

4.2.3 Calculation methods and system boundaries

In this thesis, three calculation methods NS 3720, FutureBuilt Zero, and TEK 17 are looked into. When applying different calculation methods and system boundaries to the same object, results can defer quite distinctive.

Comparison of Option A - D for NS 3720, FutureBuilt Zero, and TEK 17

Figure 4.9 presents a comparison of the calculation methods of NS 3720, FutureBuilt Zero, and TEK 17 while applying the system boundaries presented in the methodology. For this comparison, Option A to Option D, described in the methodology and depicted in Figure 3.2, are calculated.

There is a significant difference between the three calculation methods for total assessed GWP. In the presented cases NS 3720 has the highest GWP, while FutureBuilt Zero assesses the GWP to be about 15% lower for all the options. TEK 17 is in the middle of the two extremes.

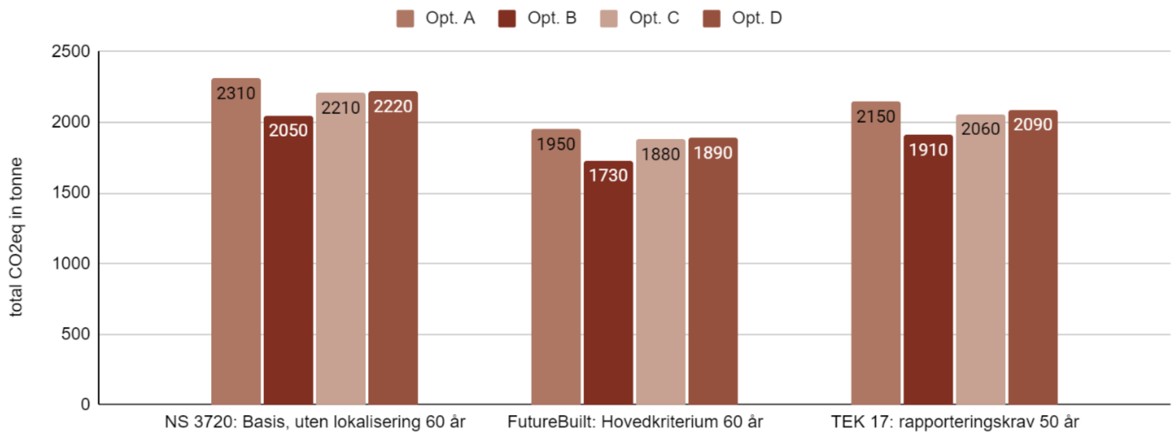


Figure 4.9: Comparison of the total GWP of Opt. A - D calculated with the calculation methods and system boundaries from NS 3720, FutureBuilt Zero, and TEK 17.

Comparison of Option A for NS 3720, FutureBuilt Zero, and TEK 17 with life cycle stages

Figure 4.10 takes a closer look at Option A in relation to the three different calculation methods, NS 3720, FutureBuilt Zero, and TEK 17 and presents the results divided into the life cycle stages. This comparison visualizes where the difference in the calculation methods and system boundaries occur in relation to the life cycle stages.

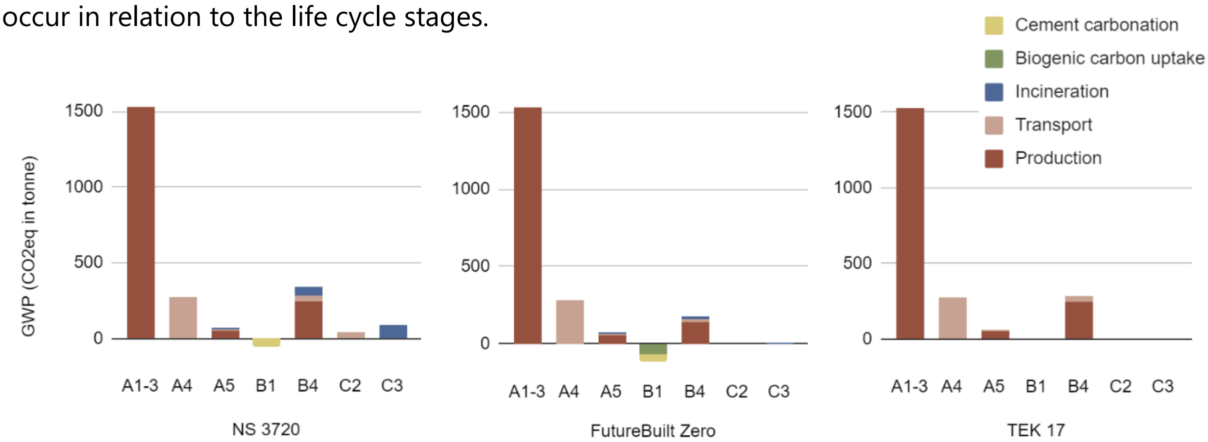


Figure 4.10: Comparison of the GWP in the different life cycle stages of Opt. A calculated with the calculation methods and system boundaries from NS 3720, FutureBuilt Zero, and TEK 17.

The emissions for A1-A3 and A4 are the same for NS 3720 and FutureBuilt Zero. TEK 17 only defers to a minor account. The life cycle stages A5, B and C show larger differences.

4.2.4 Reuse, reusability, and longevity

In Reduzer there is the option to choose reused and/or reusability for a material. NS 3720 includes reused in its calculation but excludes reusable. FutureBuilt includes both options and also allows for choosing reused and reusability for the same material.

Reuse and reusability of brick

The reuse, reusability and longevity of brick are mentioned by the interviewees. To test out how this is considered in FutureBuilt Zero a square meter of 108mm thick brick is analysed regarding the GWP and the deduction coming from reuse and reusability. The result is depicted in Figure 4.11.

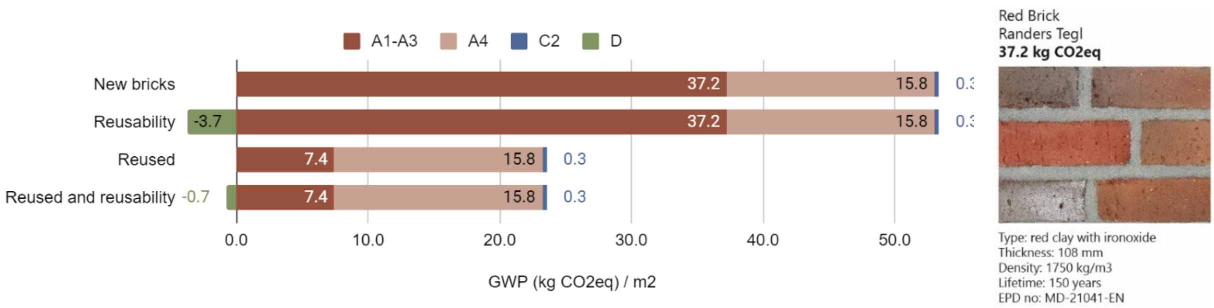


Figure 4.11: Comparison of the GWP of new bricks to reusable and reused bricks.

To give a comparison to other another cladding material, a timber cladding component with substructure is created in Reduzer. The standard default value of the ESL is 60 years for this timber cladding, and this leads to a total GWP of 2.7 $kgCO_{2eq}/m^2$. If the ESL is set down to 30 years, the total GWP is 5.1 $kgCO_{2eq}/m^2$. These façade claddings are approximately functional equivalent to the brick wall and consider the same life cycle stages and system boundaries.

Figure 4.12 illustrates the background of FutureBuilt's consideration of reuse and reusability. If the material is reused it is accounted for with 20% of the GHG emissions of the new materials. Reusability gives a negative number in D of 10% of A1-A3.

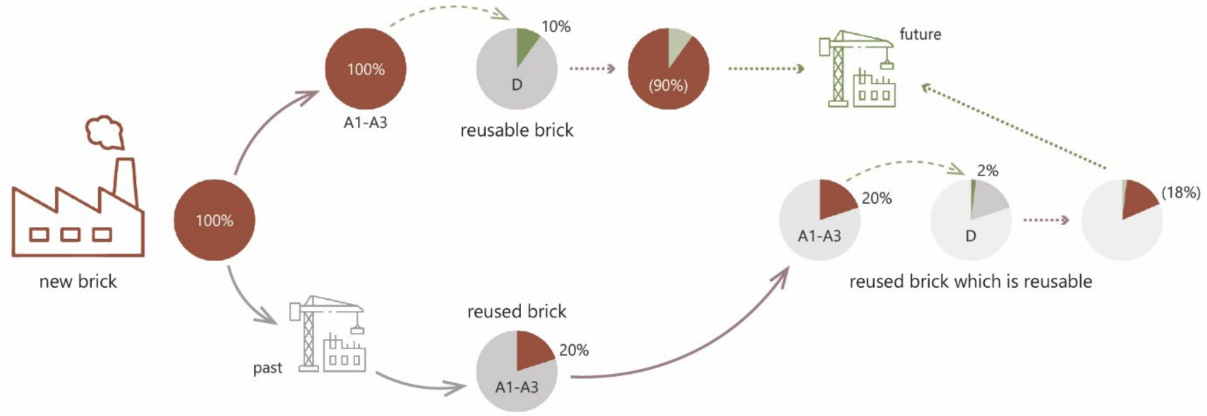


Figure 4.12: Illustration of how FutureBuilt Zero accounts for reuse, reusability, and the combination of both.

4.2.5 Shape optimization

Comparison of Option A - D

The reduction of material due to a change of shape or building size would need to be considered very early in the design phase when information is scarce. As mentioned earlier, it is recommended to use average values for the GHG emission of materials in such an early stage. The feasibility and impact are tested out with the Automodel from Reduzer on an abstract model from the classroom tract of Voldsløkka school. The created alternatives are described in the methodology and depicted in Figure 3.2. For this LCA the calculation method and system boundaries from NS 3720 are used.

The results of the total embodied emissions vary between a total of 2050 and 2310 tonne CO_{2eq} (see Figure 4.9, NS 3720) and 360 and 380 $kgCO_{2eq}/m^2$. Both the total GWP and the GWP per square meter are important to evaluate the performance. To depict both functional units as well as the information about the BTA, the bubble charts in Figure 4.14 are created.

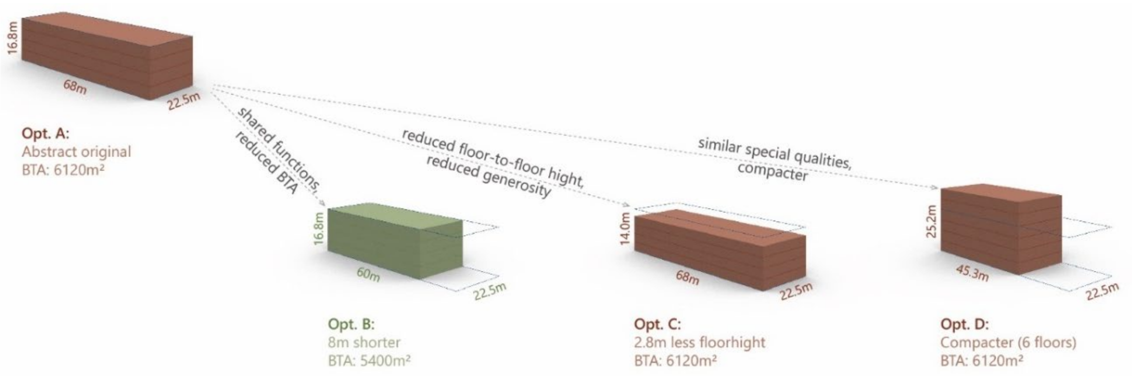


Figure 4.13: Illustration of Opt. A - D and the relation of their architectural qualities.

The four options are regarding their special qualities not equal. Options A and D should have similar special qualities as they both have the same BTA and floor-to-floor height. Option B might forfeit some qualities by sharing functions or giving less space to certain functions. Option C saves material by reducing the floor-to-floor height which might make some spaces cramped and reduce the possibilities of reuse. The potential architectural qualities or shortcomings compared to Option A are depicted in Figure 4.13.

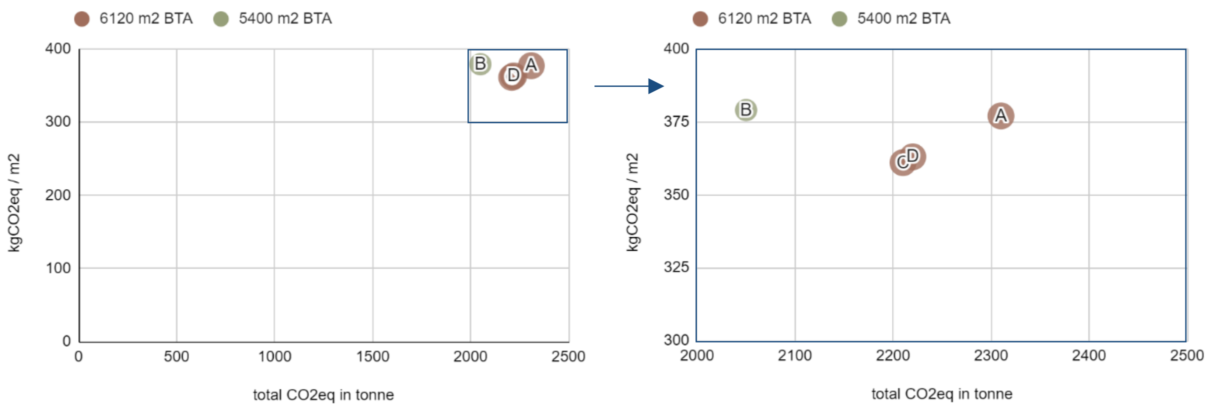


Figure 4.14: Bubble charts comparing Opt. A - D regarding their total GWP and GWP per square meter. Left: Chart starting at zero. Right: Zoom-in on the relevant area.

4.2.6 Load-bearing systems and their materiality

There is a vast amount of possibilities regarding the load-bearing system of a building. Frame building systems, solid construction systems and combinations of the two. When conducting LCA comparisons of different buildings systems numerous options can be compared. Trying to do considerations regarding the load-bearing system detached from the rest of the building elements has some difficulties. A large variance is possible and they would need to be explored for each building proposal separately. Without further information from the structural engineer, more precise calculations cannot be done, as the dimensions have an influence on the quantity, and this is influencing the embodied carbon.

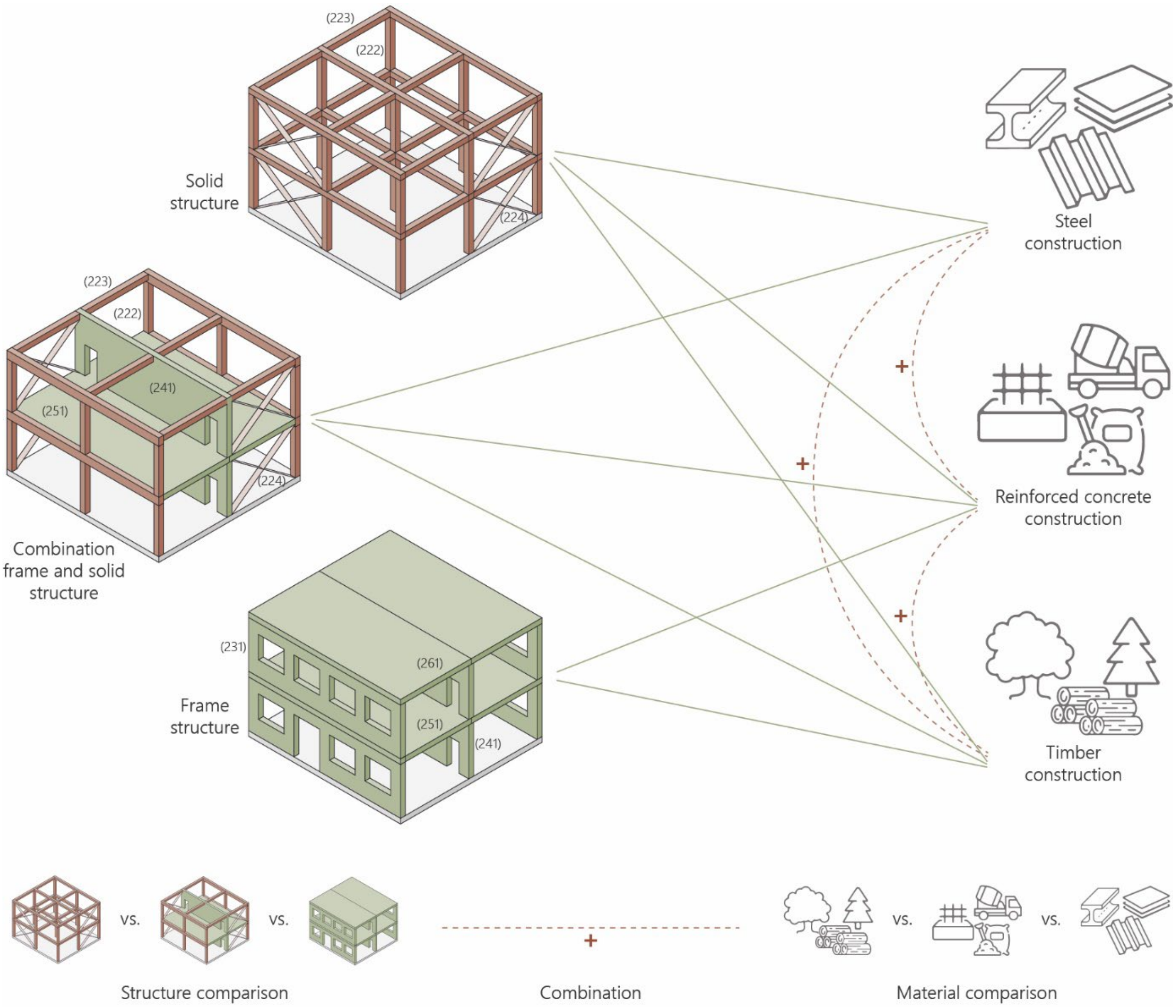


Figure 4.15: Illustration of different load-bearing systems and material choices.

5 Discussion

By investigating how embodied carbon is integrated into architectural designs, it is possible to gain valuable insights on how to impact the design process in order to improve integration and the result of the environmental impact. In this chapter, the findings from the interviews and the Embodied carbon considerations and LCA calculations chapter are discussed in light of the theory presented in the Background chapter.

5.1 Architectural design process and involved parties

The design and planning process of a building is a lengthy and complex task, in which, various parties are involved. The fundamental framework of building processes has similarities but cannot be clearly defined. A project usually starts with a general idea or need, which leads to the first drafts and sketches. It goes through different phases of options and variants, adjustments, optimizations, discussions, etc. where, through this process, the project gets more and more detailed and structured. If it does not get cancelled along the way, the final result is usually a finished building.

The interviews gave some input on how projects are currently being developed. Although they show that each design process is highly individual and a clear structure is difficult to define, some interesting aspects got pointed out during the interviews. These aspects are illustrated in Figure 5.1.

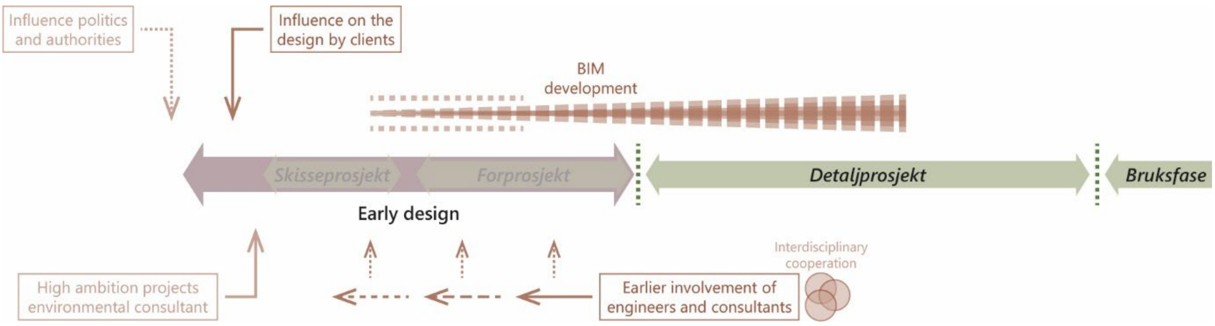


Figure 5.1: Illustration of the information from the interviews and literature regarding the design process and the involved parties.

Topic A: Structure of the design process

The literature research introduced ways of structuring the design process in the Norwegian context. Bygg21 and DFØ's building process both give lengthy explanations of the work tasks in the different stages. The naming of the stages is rather descriptive and does not allow for easy use in the colloquial language. This could be one reason why none of the official terms got mentioned in the interviews but instead, the terms *Skisseprosjekt, Forprosjekt* and *Detaljprosjekt* were introduced. These specific terms are used in DFØ's description of the "Concept development and processing stage" and are linked to the Bygg21 stages by BREEAM-NOR (see Figure 2.1).

The interviews revealed an unclear, individual structure with inconsistent terminology. One reason could be the language barrier, where it feels unnatural to use Norwegian terms in an English interview. The translation of *Detaljprosjekt* to Detailed design comes quite naturally. A possible translation for *Skisseprosjekt* could be "Conceptual design" and for *Forprosjekt* "Schematic design", but those feel less natural and straightforward. Another reason for the missing structure could be that the architects and engineers do not implement a strict structure. Additionally, the transition between *Skisseprosjekt* and *Forprosjekt* seems quite fluid which would not help to define a clear structure. In the interviews mainly the term "Early design" was used to describe the tasks before the *Detaljprosjekt*, which at least gives some hints when in the process specific topics are considered.

The Voldsløkka school project confirms that the terms *Forprosjekt* and *Detaljprosjekt* are used in practice. Furthermore, the translation of the Norwegian transcripts to English underlines the point that a clear translation is difficult.

Topic B: Involvement of the AEC and clients

In the interviews, it got mentioned that the clients have a large influence on the project, and this early on. It is also mentioned that some clients see an advantage in investing in sustainable buildings. Both findings are confirmed by literature (Hegger, et al., 2012). When aiming for higher ambitions than the current regulation BREEAM-NOR can be a label chosen. In their guidelines, they specifically state that the orientation of the design brief towards sustainability needs primarily to come from the client (Grønn Byggallianse, 2022). Interviewee #1's proposal to try to allocate the pressure points regarding environmental impact and with that knowledge try to lead the client in a sustainable direction is honourable and might convince some clients and give the architectural office a better reputation. Nevertheless, risks like working additional hours without financial compensation and upsetting the client with unwanted inputs need to be considered.

To get a wider range of building projects to implement embodied carbon assessments and optimizations in their considerations, it is up to politicians and authorities to regulate the building industry and set stricter requirements. Norway is taking a first step in this direction with the implementation of TEK 17 §17-1. However, a calculation at the final stage of a project has no impact on the performance and might be seen as a waste of time and resources. TEK 17 §17-1 is meant to increase the knowledge of LCA in the building sector, but it is not quite sure if the architect offices will be the ones gaining any experience in conducting simple LCAs. It might be that in this setting only environmental consultants and contractors developing the *Detaljprosjekt* are benefitting.

The level of involvement of engineers and consultants, as highlighted by the interviewees, varies significantly depending on the specific project requirements and context. The interviewees see a tendency for a more interdisciplinary approach in projects with environmental goals. Research recognizes this tendency towards including engineers earlier in the design concept (Hegger, et al., 2012). In Figure 2.2, it can be seen that the involvement of all players increases in the proposed planning and usage process for the future. It is interesting to notice, that the environmental consultant is in Figure 2.2 not a player in the design process. When including the environmental consultant, the graphic would most likely be similar to what is depicted in Figure 5.2. The involvement would depend on the ambitions of the project. The more ambitious a project would be the earlier the expertise from the environmental consultant would be included. According to the interviews, BREEAM-NOR and FutureBuilt it is hard to do a high-ambition project without involving an environmental consultant from the early project development.

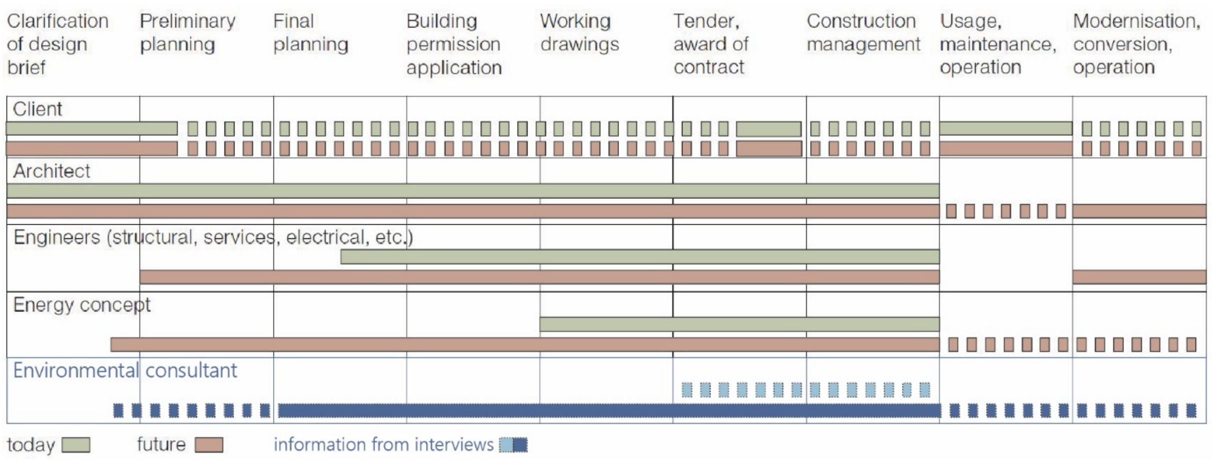


Figure 5.2: Players in the planning and usage processes, today and in the future with the environmental consultant as an additional player.

Graphic created by author based on (Hegger, et al., 2012), supplemented with information from the study.

There are clear advantages to increasing the interdisciplinary working structure in the early design stage. The architect can develop the concept with the expertise and knowledge provided by the engineers and consultants. Nevertheless, there are also reasons why it is not done universally. One could be, that involving engineers and consultants creates costs, which the client and architect are likely to try to avoid in the early stage. Striking the right balance between incorporating expert inputs in the early stages of a project, which contribute to a well-developed concept, and managing the potential risks associated with project cancellation can be challenging. Another reason could be that engineers are trained to find the best solutions for one specific problem, which clashes with the uncertainties and endless options in the early stage. Some architects might argue, that involving the technical aspects of construction limits the creative work of a design in the early stage and with that new out-of-the-box solutions are less likely. However, it can be seen that in projects with higher ambitions towards sustainability, architects lack the knowledge to take reasonable assumptions to improve the concept and design towards a lower environmental impact. It can be assumed that the design process will change towards an increased interdisciplinary workflow in the future. Nevertheless, it would be an advantage if architects know the basics of lowering embodied carbon emissions in the early stage so they can make educated decisions with limited inputs from the engineers and consultants.

Topic C: Usage of BIM in the design process

In the interviews and literature, there can be found a common understanding that BIM is a tool with the potential to facilitate LCA calculations with the required information and enhance the data collection process. The usage of BIM in early design development is a more controversial topic. Thresholds against BIM in early design development could be its time-consuming nature, the troublesomeness of creating variants and its limited flexibility. Architects are trained to develop projects through fast sketches, conceptual outlines, and a fast variety of different options, which goes against the more detailed development of a BIM model. The same arguments can be found in the literature by Hollberg & Ruth (2016). Additionally, the data exchange interface between BIM in a more conceptual stage and the LCA program, for example Reduzer, is still under development.

5.2 Integration of LCA into the design process

Embodied carbon assessments and considerations regarding lowering emissions are a rather new topic. Buildings in Europe have been optimized regarding their operational energy consumption. This has influenced the buildings' general shapes and orientations, electrical installations, heating and cooling systems, and building envelopes. Architects have become better to integrate these considerations into the design process, but often technical solutions solve the problems of suboptimal design decisions as an add-on to the building concept.

It can be argued that the same approach is possible for embodied carbon considerations. In that case, architects would plan the building mainly considering aspects like room feeling, function placement, and how the building looks. However, it is important to acknowledge that there are limitations to the extent of emissions reduction achievable through this approach. Furthermore, an architectural project might improve and sharpen its overall concept when integrating embodied carbon considerations. But the early integration of LCA into a design project always leads to the problem that embodied carbon considerations should be integrated when little information is available but the potential for optimization is increased.

Figure 5.3 depicts the information regarding the integration of LCA in the design process gained through the interviews and background research.

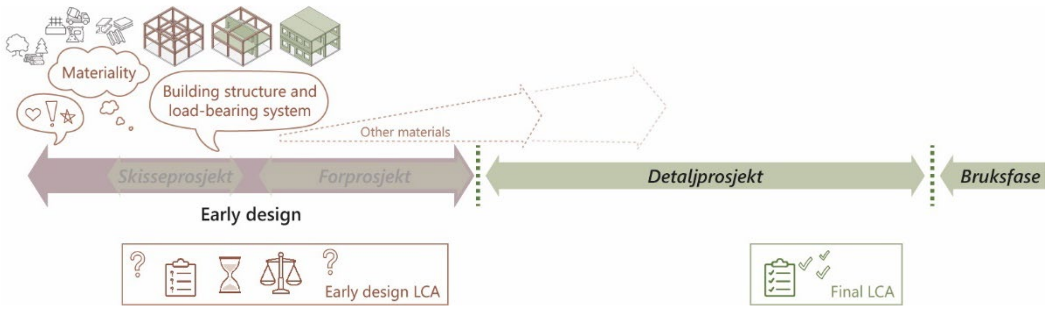


Figure 5.3: Illustration of the information from the interviews and literature regarding the integration of LCA in the design process.

Topic D: LCA calculations during the design process

The interviews emphasize the difficulties regarding meaningful early design assessments which account for the uncertainties and lack of knowledge. This is an understandable issue and is confirmed by literature. Hollberg & Ruth (2016) point out the discrepancy between the importance of the early stage regarding the possibility of influencing the emissions with little cost and work impact, and the limited knowledge about the building design (see Figure 2.10). Nevertheless, altering this discrepancy appears challenging, making it more prudent to explore strategies for working with limited information and making informed assumptions during the early stages of a project. A common problem can be that LCA presented by literature often explains how to conduct comprehensive LCA calculations with detailed data collections (see Figure 2.6) but fail to provide guidance on how to perform simplified LCAs with limited information and numerous uncertainties.

Braune & Durán (2018) recommend using average values for LCAs in the Draft planning, most likely around *Forprosjekt* in the Norwegian context. The assessments should be done for various design options and mainly concentrate on certain constructions (see Figure 2.11). While this advice appears promising and relevant, its implementation requires easy access to average values and data limitations specific to the focused construction. For this, architects would need more streamlined approaches to incorporate this information effectively and within a reasonable timeframe. Furthermore, when narrowing the scope into limited aspects, caution is required to ensure functional equivalent comparisons and keep the overall picture of the building's life cycle performance in mind.

Reduzer has acknowledged the need for early design tools and is currently developing an Automodel function which can be linked to templates containing information regarding quantities and materiality. As this function is still under development, the influence on the shape is at the point of the thesis rather limited. Fortunately, further updates and functions are planned by Reduzer to give larger freedom in the shape of the abstract building shapes. Another restraint to the Automodel is the limitation in templates and difficulties in modifying the templates. The comparisons done in this thesis with the Automodel give a glance towards the possibilities, but the current limitations in the function would most likely prevent meaningful implementation in practice.

The interviewees mention simplified material documentations like the Construction Material Pyramid, Unboxing Carbon, and the *Grønn Materialguide* as decent tools to get a better understanding of the embodied carbon in building materials. They especially see value in these tools for pre-sorting choices and general overviews for early design decisions. At first glance, these documentations offer a simple and easy-to-understand visualization of the embodied carbon of various materials. However, a closer look show that even here, deeper knowledge is required to understand the bigger picture. Because of their simplification, some important aspects like the functional unit, the concentration on life cycle stages A1-A3, and biogenic carbon in material need to be kept in mind. It can be said, that even simplified tools need some in-depth knowledge for a comprehensive understanding.

The Construction Material Pyramid give a clear relatable overview of certain materials. It even allows to switch between different functional units. But as the example of comparing the performance of foam glass, stone wool, and glass wool in relation to different functional units shows (Figure 4.2), caution regarding the most meaningful functional unit is essential. If only considering the functional unit $kgCO_{2eq}/kg$ without any further thought, foam glass would be chosen over stone wool and glass wool, although both of them perform much better than foam glass when looking at the functional unit $kgCO_{2eq}/m^2$ insulation with u-value 0.15 W/m^2K. The simplified presentation of information might be misleading towards the knowledge required to make informed and educated comparisons when using this seemingly straightforward tool.

When consulting simplified tools, one also needs to be careful about what they include and the potential impacts of excluded factors. The consideration regarding the transport distance of brick demonstrates this (Figure 4.4). In that case, the exclusion of stage A4 has a larger impact on the environmental footprint of the material. This might again lead to incomplete or incorrect conclusions and shows the limitations of simplified tools.

The inclusion of biogenic carbon uptake into these documentations adds another question mark. The Construction Material Pyramid and Unboxing Carbon include biogenic carbon without providing more insight into the topic. In contrast to this, the *Grønn Materialguide* includes information about the performance with and without the inclusion of biogenic carbon uptake. Through the incorporation of the biogenic carbon in stage A1-A3, as the simplified documentations do, timber and bio-based materials seem to perform extraordinarily well (Figure 4.5). If biogenic carbon uptake is included in A1-A3 as a negative number from the growth of the bio-based material, the emissions from the waste handling in stage C should set this uptake to zero (Figure 2.8). In the -1/+1 approach presented by Hoxha, et al. (2020), the balance of biogenic carbon uptake and release within the building's life cycle is supposed to be zero. Without an in-depth understanding of biogenic carbon uptake and how it can be included or excluded from the calculation, an educated assumption regarding the performance of the materials might be difficult. The *Grønn Materialguide* in combination with the Construction Material Pyramid can be used to demonstrate the problem around simplifying biogenic carbon in material (Figure 4.6). When including biogenic carbon in the three compared materials, the two containing bio-based products perform best. However, when the biogenic carbon is excluded the gypsum board would be the preferred choice regarding embodied carbon. The comparison between the Gypsum board, the Plywood board and the MDF board demonstrate how quick decisions and too simplified data might present an incomplete picture.

Topic E: Choices during the design process

Through the interviews, some hints on which choices are taken during the design process can be found. An aspect that was mentioned is the early consideration of materiality, which begins in the initial phases of a project. Considering the significant impact of materials on the LCA of embodied carbon, it is beneficial that the materiality is already thought about early in the project. Nevertheless, it would be an advantage if architects would obtain an intuition regarding the impact of different choices and materials. According to Hollberg & Ruth (2016) and Basbagill, et al. (2012), intuition and knowledge in the architectural community are scarce. As already discussed with the simplified tools, it can be quite difficult to find and analyse generalisations and simplified information without having some knowledge about LCA.

Another finding from the interviews is that the primary aspect to prioritize and determine in terms of materials is the building structure and load-bearing system. It is elaborated that this is decided early in the design process and has a large influence on the building's concept and shape. Due to this, it is most likely very difficult and expensive to adjust the load-bearing system at a later stage. Hence, the potential embodied emissions of these building elements should be considered in the early design stage. In this stage comparisons and a broader understanding of the building's emissions is helpful according to the interviewees. When looking at the load-bearing system comparisons of different materials are difficult. The dimensions need to be reasonable which usually means a structural engineer would need to be involved. As mentioned before, it is not always the case that a structural engineer is involved in the early design stage of a project. Furthermore, various combinations of materials and different building systems can be combined and evaluated (Figure 4.15). Considering all of this while developing multiple alternatives is time intensive and, in some cases, might not be feasible.

One strategy could be that a timber-based system, as the material which is most likely to have the smallest embodied emission, would set the starting point for a design. This strategy was implemented in the example given by interviewee #3 and the Voldsløkka school project. Timber seems also to have the largest limitations regarding large spans, stiffness within the structure, availability in Norway, and cost. When the limitations of the timber-based system's properties are reached, the introduction of alternative materials can be considered to compensate for and overcome these limitations. However, an argument against this strategy can be the most likely more labour-intensive and less straightforward aspect of this approach.

5.3 Embodied carbon considerations and influence

Although not explicitly mentioned during the interviews, an important aspect that became apparent when examining various LCA calculations is the significant influence of calculation methods and system boundaries on the resulting LCA outcomes. It is important to keep in mind that every assessment is only an assumption of potential emissions based on the information provided to the calculation software. It can be argued that the chosen calculation method is not too important, as long as it is used consistently and only LCAs considering the same method and system boundaries are compared. However, by setting certain conditions in the calculation method and system boundaries, preferences and weight are set.

When comparing the calculation methods NS 3720, FutureBuilt Zero, and TEK 17 with the example of the Automodel, it can be said that the ranking of the different Options stays the same, as well as the difference between the Options (Figure 4.14). Meaning, in the discussed example there is a difference between the results of the calculation methods, but within the same method, the relation of the result to each other stay the same. This is not always the case. By looking at one Option (here Opt. A) in detail it can be seen where the differences between the calculation methods lay Figure 4.10). While TEK 17 excludes many life cycle stages as well as cement carbonation, biogenic carbon uptake, and incineration, the two others include more stages. This limited scope of TEK 17 is most likely the main reason behind the lower GWP compared to NS 3720. FutureBuilt Zero scope includes more aspects in the analysis while also incorporating benefits in the form of biogenic carbon uptake, and anticipated technological advancements in the future, leading to a reduced GWP. Additionally, it needs to be kept in mind that the Automodel from Reduzer only includes information about the building elements (22)-(26), and (28). Because of this limited information provided in the model, there is only a minor difference (element (28) is excluded from TEK 17) in the considered elements, although the system boundaries regarding the considered elements show a larger variety.

It should be pointed out that Option A to D use the same template, meaning there is a difference in quantities but not in the material choices. This is most likely the reason for the same ranking within one calculation method. A change in materiality within the comparison can have an influence on the conclusions drawn, depending on the calculation method. This can be seen in the comparison of the two cantilevered slabs (Figure 4.8). Since FutureBuilt Zero includes biogenic carbon uptake in its considerations the building element containing more timber performs better. When comparing the two elements with the calculation method NS 3720, no clear preference can be drawn. This shows how difficult it is to compare buildings regarding their embodied carbon if the methods and system boundaries are not clearly defined and followed.

Topic F: Material choices

When choosing materials, architects not only focus on low-carbon materials, but also on factors like recycling, reuse, and longevity which can help to reduce the embodied carbon of buildings. Interestingly, there was a notable consensus among the interviewees regarding their current priorities in material selection and the factors that could effectively reduce embodied carbon. This overlap might be related to the fact that the interviewees were aware of the topic of interest. Unbiased participants might have shown a different focus in their answers. Durability, reduction of needed repairs and replacements, reuse, and design for disassembly are related to this topic and advertised in BREEAM-NOR's Mat 05 to Mat 07. It is important to notice how early these considerations should be integrated into the design process and that they remain important throughout a project (Figure 2.12).

When calculating the benefits of reuse and recycling it is important to keep in mind that these are theoretical numbers which try to give benefits for something difficult to account for. The accounting within FutureBuilt Zero for reuse, reusability, and the combination of both is illustrated in Figure 4.12. The comparison depicted in Figure 4.11 shows how much embodied carbon can be saved when reusing. Interestingly, by reusing bricks the transport (A4) can become the most emitting life cycle stage. The standard default value for the transport distance of brick is 500 km, which leads to 16 $kgCO_{2eq}/m^2$ brick wall which accounts for double of the remaining 20% for the brick itself. However, when implementing reuse and emphasizing low emissions, it might be worth exploring other alternatives that may have even lower emissions. While it can be argued that the accounting for the brick in stages A1-A3 is an assumption, the emissions caused by transport are more real and significant. So, unless the transport distance is below 160 km the timber cladding performs better even if it would be exchanged once in the 60-year life cycle. Comparing brick cladding with timber cladding might be a bit far out as it is very likely more pressing arguments for the brick cladding than the emissions.

The interviewees mention timber as a favourable low-carbon material. The perception that timber structures are less embodied carbon intensity compared to steel or concrete is confirmed by the study carried out by Saade, et al. (2020). It is important to notice that this study does not state clearly how biogenic carbon uptake is considered in the calculations. Furthermore, the study is limited to framed building systems and gives no insights into how solid structures would perform.

Biogenic carbon uptake is an important consideration to include when stating that timber constructions perform better compared to concrete and steel. The comparison of the CLT slab with floor build-up to the concrete hollow-core slab with the same floor build-up (Figure 4.7) can be used to illustrate this (Figure 4.8). When comparing the two components with a calculation method which excludes biogenic carbon uptake (NS 3720) it can be seen that the two components only have a minor difference of 1 $kgCO_{2eq}/m^2$. Including the biogenic carbon uptake with a dynamic calculation method (FutureBuilt Zero) changes the results drastically. Additionally to the generally lower GWP calculated by FutureBuilt Zero comes a more distinct difference between the two components. The CLT slab has according to the FutureBuilt Zero assessment a 17 $kgCO_{2eq}/m^2$ lower GWP compared to the concrete hollow-core slab, wherefrom the biogenic carbon uptake is responsible for 15 $kgCO_{2eq}/m^2$. It needs to be kept in mind, that this one comparison is not enough to draw a generalisation, but it demonstrates what influence the different calculation methods can have. Also worth mentioning is that timber is only a regenerative material when the forestry is driven in a circular sustainable fashion. FutureBuilt Zero calculates the carbon uptake from the tree which is replacing the tree which got transformed into construction material. The uptake only happens when the tree is replaced. If this does not happen the biogenic carbon uptake inclusion in the calculation can be considered as greenwashing or an unjustified benefit of timber and other bio-based products. Simplified documentations like the Construction Material Pyramid and Unboxing Carbon might oversell the potential of timber. However, more detailed calculations like the dynamic approach to evaluating biogenic carbon uptake provide a rather robust and transparent evaluation according to research (Hoxha, et al., 2020).

The interviews find concrete and steel as preferred materials by engineers, consultants, and clients due to their widespread familiarity and extensive usage. Nazari & Sanjayan (2017) highlight concrete as the most commonly used construction material globally. The composite material reinforced concrete grants great creative freedom in regards to formability and low cost, which is most likely something which is cherished by many architects as well as clients and structural engineers. Interestingly, the interviews emphasize that clients and economic experts favour concrete and steel structures due to their greater experience with these materials. It is noteworthy that not only the actual cost but also the perceived risk can play a crucial role in decision-making. The interviews also point out that structural engineers might have a similar tendency towards concrete and steel structures. It appears that their expertise and experience lie predominantly in the calculation and design of concrete and steel structures. Consequently, it might be challenging for an engineering office without prior knowledge or expertise in timber structures to confidently develop robust concepts, assumptions, and calculations for a timber-based design. This leads to the assumption, that it is difficult to realise a timber-based construction if client and structural engineer are not on board with it from the very early stage.

Consulting the example of the Voldsløkka school project, low-carbon buildings can contain a rather large amount of concrete and steel. Possibilities to lower the embodied carbon in these materials could be, as done in the Voldsløkka school project, to use low-carbon-concrete, recycled reinforcement, and recycled steel. Limitations of implementing these measures might be missing availability, larger cost, and reduced static properties.

Bricks appear to be a controversial topic when it comes to discussing the large embodied carbon of the material. The Unboxing Carbon Catalog shows the variety of bricks in relation to their GHG emission in stages A1-A3, which spans from 10.7 $kgCO_{2eq}/m^2$ to 60.1 $kgCO_{2eq}/m^2$ (Henning Larsen, 2022). The three standpoints from the interviews are: One, the longevity makes up for the large emissions. Two, longevity does not justify the large emissions. Three, only use brick if necessary and be cautious about choosing a material with low embodied emission or reuse. How the longevity and the possibility of reuse and reusability affect the GWP of the material has been discussed previously. It feels important to underline here that, it is up to the individual project to weigh the advantages of the material to the related embodied carbon emissions. A generalisation is difficult to make. Reasons for using brick could be, the monumental expression they give to a building, or to fit a building into an existing context. Using brick-like cover-ups is usually less popular with architects due to the wish of many architects to stay true to a material choice and not use blending materials. Additionally, an architect's aim might be, that the designed building lasts for a long time, but the future is not predictable, and emissions need urgently to be lowered now. The unpredictability of the future should be a factor in the decision process. Nevertheless, it is not possible to just ban large emitting materials in order to avoid emissions. A prudent approach could be to acknowledge the significant emissions and limit the use of bricks to cases where local reuse is feasible or to areas where bricks with low embodied carbon are manufactured nearby. The long tradition of using brick as an outer cladding material will most likely not change only because people get aware of the large embodied carbon emissions, but it might be used with more caution.

Topic G: Inputs on how to lower embodied carbon

The interviewees mention the reduction of material use as one possible way of optimizing the GWP of an object. They propose to design compact buildings, reduction of built square meters and reuse existing building mass. All these measures would need to be considered in the initial design phase, hence with very limited information. As discussed earlier, the shape would also need to take some pre-considerations regarding the materiality of the load-bearing system and the connected limitations (Figure 4.15). Although the Automodel from Reduzer has at its current stage considerable limitations, it can be used to demonstrate how a shape optimization could look like, and what impacts need to be considered. Figure 4.13 and Figure 4.14 present this experiment. Some measures might not be feasible due to preferences by the client or restrictions within the building standard or site. When comparing the different possibilities and options a comprehensive approach should be chosen. For instance, comparing Option A to Option B regarding the functional unit $kgCO_{2eq}/m^2$ shows no optimization, but when looking at the total GWP Option B performs better, due to the smaller BTA. Another aspect which needs to be weighed is the architectural consequences of the optimization. Option C and Option D result in similar values when assessing in regard to GWP per square meter as well as the total GWP. However, the reduction in floor-to-floor height in Option C might have a significant influence on the architectural quality of the spaces. This analysis is difficult to do in a number-based manner but is more of an intuitional balancing of different factors and consequences.

Another suggestion to lower embodied carbon is to limit the construction of basements and foundations to a minimum. These considerations are very important to do early in the design as it is the base for the rest of the building. Basements and foundations are usually containing large quantities of reinforced concrete in combination with plastic to seal the building off against water and moisture from the ground. As discussed before, there are options to also lower embodied carbon emissions in reinforced concrete.

Encounter other characteristics than only the low embodied carbon in building materials is highlighted as another potential saving measure. Some aspects like reuse, recycling, reusability, and longevity have already been discussed in this thesis. Further aspects could be the development of details which allow for easy maintenance and enable future disassembly. As mentioned before, Mat 05, Mat 06, and Mat 07 in BREEAM-NOR emphasize these aspects of environmental impact reduction (Grønn Byggallianse, 2022). However, as stated by interviewee #5, the effort put into the possible adjustment for the future needs to be in relation to the uncertainties of disassembly, reuse and recycling actually happening. Nevertheless, planning for uncertainties is part of any architectural design and needs to be integrated into the considerations as well as possible.

6 Conclusion

This master's thesis set out to explore the integration of embodied carbon assessment in architectural design. For this, the current practice of structuring an architectural design process in Norway, and the integration of LCA considerations into this process are investigated. This thesis also explores opportunities for influencing and improving the integration and performance of embodied carbon assessments by architects during the design phases.

Five semi-structured interviews with architects and engineers were conducted in order to obtain insights. Additionally, four interviews from the Voldsløkka school project with individuals involved in the design and planning process were analysed to supplement the information obtained from the thesis-specific interviews. The findings from the interviews were complemented by detailed examinations of various considerations related to embodied carbon and LCA calculations. These additional considerations provide insights and address controversies and uncertainties identified during the interviews.

The development of architectural designs is contingent upon the specific project and the parties involved. Generally, the client plays a significant role in shaping the environmental optimization opportunities of a project, by influencing early decisions regarding demolishing or refurbishing, materiality preferences and the establishment of the design brief. Moreover, the client often sets the environmental aspirations for the project. The findings of this thesis also indicate a tendency towards an increase in collaborative work between architects, engineers, and consultants within projects with higher environmental ambitions.

The integration of LCA into the design process is a developing field. While there is an awareness of the topic amongst architects, there is still a lack of streamlined approaches to effectively incorporate LCA information into the design process. Reduzer, as a software application, is actively improving its program to provide a user-friendly interface that appeals to architects and their working methods. However, there are opportunities for further optimizations, particularly in relation to the Automodel feature and the availability of templates. The discussions and insights regarding embodied carbon assessments highlight the need for a deeper knowledge and understanding of this topic to successfully implement LCA in the early design stages. While architects can rely on environmental consultants for expertise in this area, an optimized approach would involve architects gaining elementary knowledge about LCA considerations for early design. To facilitate this approach, information should be made more readily available and presented in an enhanced way compared to current practices.

The greatest potential for improving the embodied carbon impact of a building lies in the initial stages of the design process. Key factors that can be influence are foundation and basement reduction, load-bearing systems and building structures optimization, and including material characteristics like low embodied carbon, longevity, reuse, and reusability into the considerations. However, there is a need for further advancements in understanding how to effectively conduct these assessments with the limited information and strict timeframe of an early design, so that several alternatives can be tested for informed decision-making.

Enhancing the integration of LCA in the design process would greatly benefit from clear and more stringent benchmarks. Relying solely on the goodwill of clients and stakeholders leaves room for factors like personal preferences, cost considerations, and perceived lower risk to dominate decision-making. Architects must acknowledge that addressing embodied carbon is a complex and challenging task, requiring effort to grasp its intricacies. Simultaneously, researchers and engineers should strive to communicate LCA concepts in a more accessible manner, ensuring that architects are not overwhelmed by the vast amount of information and various calculation approaches.

The selected methodology for this master's thesis provided a comprehensive understanding of the topic. However, the vast number of aspects concerning LCA, together with the individuality of each project development process constrained the findings and conclusions to general statements.

Further research could delve into how high-ambition projects effectively incorporate embodied carbon assessments into their design processes and explore strategies for integrating these considerations into a broader spectrum of architectural projects. Additionally, future studies could focus on developing supportive frameworks or tools to assist architects in seamlessly integrating embodied carbon considerations into building design, while also addressing the challenges and trade-offs that arise during the decision-making process.

References

Attia, S., Santos, M. C., Al-Obaidy, & M., Baskar, M. (2021). Leadership of EU member States in building carbon footprint regulations and their role in promoting circular building design. *IOP Conference Series. Earth and Environmental Science, 855(1)*, 12023. doi:https://doi.org/10.1088/1755-1315/855/1/012023

Basbagill, J., Flager, F., Lepech, M., & Fischer, M. (2012). Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Building and Environment*. doi:https://doi.org/10.1016/j.buildenv.2012.11.009

BauNetz. (2023, March 12). *BREEAM: Britisches Nachhaltigkeitszertifikat*. Retrieved from Baunetz Wissen: https://www.baunetzwissen.de/nachhaltig-bauen/fachwissen/nachweise-zertifikate/breeam-britisches-nachhaltigkeitszertifikat-668527

Birgisdottir, H., & Rasmussen, F. N. (2019). Development of LCAbyg: A National Life Cycle Assessment Tool for Buildings in Denmark. *IOP Conference Series: Earth and Environmental Science, 290(1)*, 12039. doi:https://doi.org/10.1088/1755-1315/290/1/012039

Braune, A., & Durán, C. R. (2018). *Life Cycle Assessments - a guide on using the LCA.* Stuttgart: DGNB. Retrieved from https://www.dgnb.de/en/council/publications/

Brinkmann, S., & Kvale, S. (2015). *InterViews: Learning the Craft of Qualitative Research Interviewing.* Thousand Oaks: SAGE Publications.

Bygg21. (2023, April 28). *Hvor er du i prosjektet?* Retrieved from byggelig.no: https://www.byggelig.no/

Carbon Leadership Forum. (2020, December 17). *Carbon Leadership Forum - Embodied Carbon 101.* Retrieved from https://carbonleadershipforum.org/embodied-carbon-101/

CINARK - Centre for Industrialised Architecture. (2023, April 21). *The Construction Material Pyramid*. Retrieved from The Construction Material Pyramid: https://www.materialepyramiden.dk/

Context AS & Grønn Byggallianse. (2021, Januar). *Grønn Materialguide.* Retrieved from https://byggalliansen.no/kunnskapssenter/publikasjoner/gronn-materialguide-versjon-2-2/

DFØ. (2022, December 12). *Byggeprosessen*. Retrieved from Anskaffelser.no: https://anskaffelser.no/anskaffelsesprosessen/byggeprosessen/konseptutvikling-og-bearbeiding-i-bygg-og-anlegg

DFØ. (2022, December 12). *Klimagassutslipp for bygg*. Retrieved from Anskaffelser.no: https://anskaffelser.no/nn/verktoy/analyseverktoy/klimagassutslipp-bygg

Ecoinvent. (2023, May 03). *Ecoinvent - Software Tools*. Retrieved from Ecoinvent: https://ecoinvent.org/the-ecoinvent-association/software-tools/

EN 15978. (2011, November). EN 15978:2011. *Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method*. European Committee for Standardization.

Fnais, A., Rezgui, Y., Petri, I., Beach, T., Yeung, J., Ghoroghi, A., & Kubicki, S. (2022, May 04). The application of life cycle assessment in buildings: challenges, and directions for future research. *The International Journal of Life Cycle Assessment, 27*, 627-654. doi:https://doi.org/10.1007/s11367-022-02058-5

Grønn Byggallianse. (2020). *Slik lykkes du bedre med ditt BREEAM-prosjekt.* Oslo: Grønn Byggallianse. Retrieved from https://byggalliansen.no/kunnskapssenter/publikasjoner/prosessveileder-breeam-gronn-byggallianse-2/

Grønn Byggallianse. (2022). *BREEAM-NOR v6.0 New Construction - Technical Manual SD5076NOR*. BRE Global. Retrieved from https://byggalliansen.no/sertifisering/om-breeam/manual-verktoy-og-hjelp/breeam-nor-manual-og-verktoy/

Hegger, M., Fuchs, M., Stark, T., & Zeumer, M. (2012). *Energy Manual: Sustainable Architecture.* Basel: Birkhäuser.

Henning Larsen. (2022, October 31). *Unboxing Carbon - the Catalog.* Retrieved from https://henninglarsen.com/en/unboxing-carbon/unboxing-carbon-material-catalog

Hollberg, A., & Ruth, J. (2016). LCA in architectural design: A parametric approach. *The International Journal of Life Cycle Assessment, 21(7)*, 943-960. doi:https://doi.org/10.1007/s11367-016-1065-1

Hoxha, E., Passer, A., Ruschi Mendes Saade, M., Trigaux, D., Shuttleworth, A., Pittau, F., . . . Habert, G. (2020). Biogenic carbon in buildings: a critical overview of LCA methods. *Buildings & Cities*. doi:https://doi.org/10.3929/ethz-b-000432485

Huang, M. (2019). *Life Cycle Assessment of Buildings: A Practice Guide.* The Carbon Leadership Forum, Department of Architecture, University of Washington. Retrieved from https://carbonleadershipforum.org/lca-practice-guide/

IEA, & UNEP. (2018). *2018 Global Status Report: towards a zero-emission, efficient and resilient buildings and construction sector.* Retrieved from https://wedocs.unep.org/handle/20.500.11822/27140;jsessionid=C286A34BA425A5D8C155887AB0D1A86A

ISO 14010. (2006, July 01). ISO 14040:2006. *Environmental management - Life cycle assessment - Principles and framework*. International Organization for Standardization.

ISO 16739. (2018). ISO 16739-1:2018. *Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries*. International Organization for Standardization.

Lolli, N., Gaitani, N., Schneider-Marin, P., Brudal, Ø., Resch, E., Lazarevic, S., . . . Motzke, B. (2022, December 31). D4.1 Design guidelines of a climate positive circular community in Oslo. *ARV - Climate Positive Circular Communities.*

Nazari, A., & Sanjayan, J. G. (2017). *Handbook of Low Carbon Concrete*. Amsterdam: Academic Press.

Norsk betongforening. (2019). *Lavkarbonbetong (Publikasjon nr. 37)*. Oslo: Norsk betongforening.

NS 3451. (2022, March 18). NS 3451:2022. *Bygningsdelstabell og systemkodetabell for bygninger og tilhørende uteområder*. Standard Norge.

NS 3720. (2019, April 08). NS 3720:2018. *Method for greenhouse gas calculations for buildings*. Standard Norge.

OneClick LCA. (2023, March 14). *OneClick LCA for Norge*. Retrieved from OneClick LCA: https://www.oneclicklca.com/no/

Resch, E., Wiik, M., Tellnes, L. G., Andresen, I., Selvig, E., & Stoknes, S. (2022). FutureBuilt Zero - A simplified dynamic LCA method with requirements for low carbon emissions from buildings. *IOP Conference Series. Earth and Environmental Science, 1078(1)*, 12047. doi:https://doi.org/10.1088/1755-1315/1078/1/012047

Research Council of Norway. (2023, May 03). *Reduzer - accelerating the world's transition to sustainable material use and construction*. Retrieved from The Research Council of Norway: https://prosjektbanken.forskningsradet.no/en/project/FORISS/337491?Kilde=FORISS&distribution=Ar&chart=bar&calcType=funding&Sprak=no&sortBy=date&sortOrder=desc&resultCount=30&offset=90&LTP.1=LTP2+Muliggj%C3%B8rende+og+industrielle+teknologier

Saade, M. R., Guest, G., & Amor, B. (2020). Comparative whole building LCAs: How far are our expectations from the documented evidence? *Building and Environment, 167*, 106449. doi:https://doi.org/10.1016/j.buildenv.2019.106449

Scheerer, S., & Proske, D. (2008). *Stahlbeton for Beginners: Grundlagen für die Bemessung und Konstruktion*. Berlin: Springer.

Schumacher, R., Theissen, S., Höper, J., Drzymalla, J., Lambertz, M., Hollberg, A., . . . Meins-Becker, A. (2022, May 20). Analysis of current practice and future potentials of LCA in a BIM-based design process in Germany. *E3S Web of Conferences 349*. doi:https://doi.org/10.1051/e3sconf/202234910004

TEK 17. (2022, July 01). TEK 17 §17-1. *Veileder for utarbeidelse av klimagassregnskap*. Direkroratet for byggekvalitet. Retrieved from https://dibk.no/regelverk/byggteknisk-forskrift-tek17/17/17-1v

The Norwegian EPD Foundation. (2023, May 03). *EPD-Norway - Hva er en EPD?* Retrieved from EPD-Norway: https://www.epd-norge.no/hva-er-en-epd/

Weygant, R. S. (2011). *BIM Content Development: Standards, Strategies, and Best Practices*. Hoboken, New Jersey: John Wiley & Sons, Inc.

Yudelson, J. (2008). *The Green Building Revolution*. Washington: Island Press.

Appendixes

Interview Guide

Main topic A: Background information about the interviewed person

1. Main question: What kind of architectural projects have you been working on?

Follow up: What design / planning phase were you involved in?

Follow up: What types of buildings have you mainly been working on?

Follow up: Is there any of these projects which is in particular interesting in the aspects of material choices or design process?

Follow up: Did any of these projects have any certification criteria which included environmental aspects?

2. Main question: What part of a planning / building process are you most interested / involved in?

Give hints: Different design phases, different design tasks, different interactions with people, …

3. Main question: Can you tell a bit about your knowledge of LCA and GHG emissions of building materials in the building process?

Follow up: Does your office have any inhouse knowledge about LCA?

Main topic B: Planning / design process of a building project

1. Main question: Is there a "normal" way your structure a planning process in your office?

Tip: If it helps you can use the Norwegian terms.

Follow up: Is there planning structure you follow?

Follow up: Are there any milestones you usually have?

Follow up: Do you have a template or guideline you use?

Follow up: How much does the kind of project influence the planning structure?

2. Main question: What detail level does the design project have in the different phases?

Follow up: How detailed are the drawings? Any specific scales in different phases?

Follow up: How do you store the information which is not in the drawings?

3.	**Main question:**	**When do you start involving the different specialists? (engineers, fire safety consultant, acoustical expert, environmentalist, ...)**
	Follow up:	Have you had a project where you had a specialist for LCA or GHG emissions?
	Follow up:	How do you hand over information about the project to the specialists / engineers?
	Follow up:	Would you prefer to involve the specialists earlier / later? And why?
4.1.	**Main question:**	**In the questionnaire you answered that you use BIM. How is your experience with BIM? (BIM = Building Information Modeling)**
	Follow up:	Does your use of BIM include using IFC (Industry Foundation Classes) or LOD (Level of Development)?
	Follow up:	Do you use the BIM model to determine quantities?
	Follow up:	What is the main reason why you use BIM?
	Follow up:	When in the planning process do you start using BIM?
4.2.	**Main question:**	**In the questionnaire you answered that you do not use BIM. What could the reason be, why you / your office does not use BIM? (BIM = Building Information Modeling)**
	Follow up:	What tool do you instead use to determine quantities?
	Follow up:	What tools do you use instead to hand over information to your planning partners / engineers?

Main topic C: Material / building system choices in the design process

1.	**Main question:**	**When in the planning process do you start thinking about different materials / building systems?**
	Follow up:	Do you write your initial ideas somewhere down, or does it more stay in your head until you have to take a decision?
	Follow up:	When do you take the final decision?
	Follow up:	Is there a difference when the material is not the finishing layer?
2.	**Main question:**	**What are the materials / building systems you focus mainly on?**
	Give hints:	Load-bearing system, walls, finishing layers, ...
	Follow up:	By what is this focus mainly influenced?

3.	**Main question:**	**When choosing a material / building system, which factors influence the decision?**
	Follow up:	Is there a difference when the material is not the finishing layer?
	Give hints:	How does … influence the decision? Optic, haptic, maintenance, off gassing, transport distance (local resource), personal preferences, cost, fire resistance, environmental impact, …
	Follow up:	Do you follow the principle of being true / honest to the material? meaning i.e.: the load-bearing structure should be represented by the finishing layers.
4.	**Main question:**	**Are there any material / construction systems you already decide on early in the design process?**
	Give hints:	Load-bearing system, main structure, insulation system, …
	Follow up:	What are the main reasons / factors influencing this decision?
5.	**Main question:**	**How large of an influence does the client take regarding the material / building system choice?**
	Follow up:	What is the client usually focusing on?
	Follow up:	Is this information specified in the design brief?
	Follow up:	Is LCA, GHG emissions, or low environmental impact one of the factors clients talk about?

Main topic D: Design / quantity choices in the design process

1.	**Main question:**	**What is usually the main decision driver for the expression / shape of the building?**
	Follow up:	Could you imagine that environmental impact considerations would mainly shape the design / form / expression of a building?
2.	**Main question:**	**Do you have experience with refurbishment /demolishment projects? Projects where the plot included existing building mass?**
	Follow up:	What was the main decision driver for how to handle the existing building mass?
	Follow up:	How did environmental aspects lead / influence you decision process?

Main topic E: Architects’ intuition regarding LCA

1. **Main question:** **What do you think should an architect focus on in order to lower the GHG emissions in a project?**

   Give hints: Reducing footprint of the building, reducing materials containing cement, using local materials, using materials with long lifespans, …

   Follow up: How would this affect the architecture?

   Follow up: When (in which phase) should the architect spend time on LCA calculations / considerations?

   Follow up: Is there anything which you think could be very efficient?

2. **Main question:** **What material / building system do you think would lower the GHG emissions in a project?**

   Clarifying: So, you think by using more … you would emit more / less CO2?

   Follow up: Why do you think that this material / building system would help reducing the CO2 emissions?

3. **Main question:** **What information should be easily available to help you to take better decisions regarding lowering emissions?**

   Follow up: Where would you now look for this information?

   Follow up: Which knowledge about LCA do you have which you think should be common knowledge amongst architects?

Main topic F: Presentation of information

1. **Main question:** **In order to make information about LCA related design decisions more available for architects, how would you like the information to be presented?**

   Follow up: Do you have any, in your opinion, good examples?

Interview Guide - Consultant

Main topic A: Background information about the interviewed person

1. Main question: **What building / research projects have you been working on?**

Follow up: What design / planning phase were you involved in?

Follow up: What types of buildings have you mainly been working on?

Follow up: Is there any of these projects which is in particular interesting in the aspects of material choices or design process?

Follow up: Did any of these projects have any certification criteria which included environmental aspects?

2. Main question: **What aspects of LCA and embodied emissions in materials are you teaching?**

Follow up: To what kind of people?

Follow up: What background knowledge about LCA do people in your experience have?

3. Main question: **Can you tell a bit about your knowledge of LCA and GHG emissions of building materials in the building process?**

Follow up: Does your office have any inhouse knowledge about LCA?

Main topic B: Planning / design process of a building project

1. Main question: **Is there for you a "normal" way your structure a planning process?**

Tip: If it helps you can use the Norwegian terms.

Follow up: Is there planning structure you follow?

Follow up: Are there any milestones you usually have?

Follow up: Do you have a template or guideline you use?

Follow up: How much does the kind of project influence the planning structure?

2. Main question: **What detail level does the design project have in the different phases?**

Follow up: How detailed are the drawings? Any specific scales in different phases?

Follow up: How do you store the information which is not in the drawings?

3.	**Main question:**	**When in the design process do you get involved as an environmental specialist?**
	Follow up:	When is in your opinion the best time to get involved?
	Follow up:	Who takes the decides when you are getting involved?
	Follow up:	Would you prefer to get involve earlier / later? And why?
4.	**Main question:**	**What is your experience with BIM? (BIM = Building Information Modeling)**
	Follow up:	Does your use of BIM include using IFC (Industry Foundation Classes) or LOD (Level of Development)?
	Follow up:	Do you use the BIM model to determine quantities?
	Follow up:	What is the main reason why you use / not use BIM?
	Follow up:	When in the planning process do you start using BIM?
5.	**Main question:**	**When in the process do you do building material LCA calculations?**
	Follow up:	How detailed are the calculations at what stage in the process?
	Follow up:	Are there any calculations or considerations you think the architect should or could do?
	Follow up:	Where do you think there is potential for optimization for the LCA calculation or consideration?

Main topic C: Material / building system choices in the design process

1.	**Main question:**	**What is your experience with architects, when they need to choose or decide on a building material or system?**
	Follow up:	What do they focus on?
	Follow up:	What should they focus on?
2.	**Main question:**	**What is your contribution to the material or building systems choice?**
	Follow up:	Is there a formal way how you note down your decisions or inputs to the client and architects?
	Follow up:	When do you take the final decision?
	Follow up:	Is there a difference when the material is not the finishing layer?
3.	**Main question:**	**What are the materials / building systems you focus mainly on?**
	Give hints:	Load-bearing system, walls, finishing layers, …
	Follow up:	By what is this focus mainly influenced?
	Follow up:	Are there any material / construction systems you already decide on early in the design process?

5. **Main question:** **How large of an influence does the client take regarding the material / building system choice?**

Follow up: What is the client usually focusing on?

Follow up: Is this information specified in the design brief?

Follow up: Is LCA, GHG emissions, or low environmental impact one of the factors clients talk about?

Main topic D: Design / quantity choices in the design process

1. **Main question:** **What is usually the main decision driver for the expression / shape of the building?**

Follow up: Could you imagine that environmental impact considerations would mainly shape the design / form / expression of a building?

2. **Main question:** **Do you have experience with refurbishment /demolishment projects? Projects where the plot included existing building mass?**

Follow up: What was the main decision driver for how to handle the existing building mass?

Follow up: How did environmental aspects lead / influence you decision process?

Main topic E: Architects' intuition regarding LCA

1. **Main question:** **What do you think should an architect focus on in order to lower the GHG emissions in a project?**

Give hints: Reducing footprint of the building, reducing materials containing cement, using local materials, using materials with long lifespans, …

Follow up: How would this affect the architecture?

Follow up: When (in which phase) should the architect spend time on LCA calculations / considerations?

Follow up: Is there anything which you think could be very efficient?

2. **Main question:** **What material / building system do you think would lower the GHG emissions in a project?**

Clarifying: So, you think by using more … you would emit more / less CO2?

Follow up: Why do you think that this material / building system would help reducing the CO2 emissions?

3.	**Main question:**	**What information should be easily available to help you to take better decisions regarding lowering emissions?**
	Follow up:	Where would you now look for this information?
	Follow up:	Which knowledge about LCA do you have which you think should be common knowledge amongst architects?
4.	**Main question:**	**Do you have a good methodology to make information visible or better understandable?**
	Follow up:	Do you have any comparisons which you think are important to calculate in a project?

Main topic F: Presentation of information

1.	**Main question:**	**In order to make information about LCA related design decisions more available for architects, how would you like the information to be presented?**
	Follow up:	Do you have any, in your opinion, good examples?

Appendix 3: Spreadsheet for information from interviews

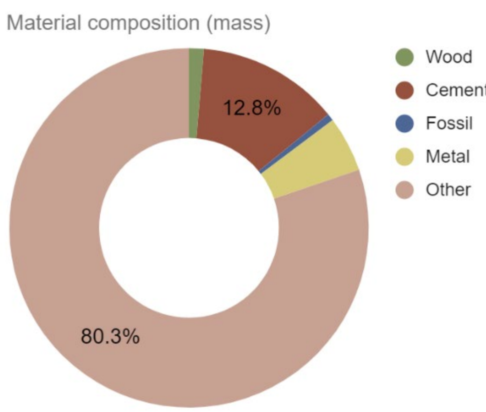
Submitted as a digital appendix.

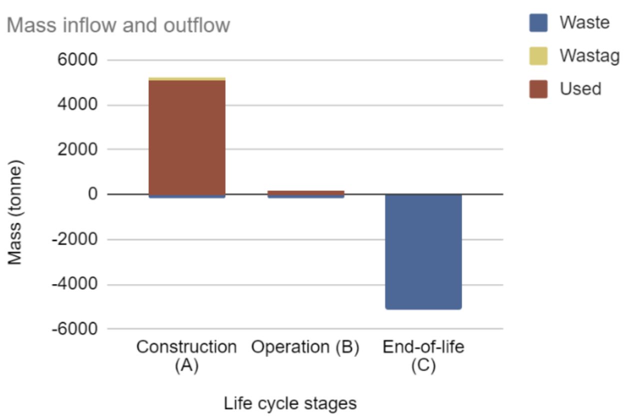
File name: Appendix 3 - Information overview from interviews

Inventory Option A - D

Element	Description	Unit	Service life (yrs)	Transport distance (km)	Mass (kg) Option A	Mass (kg) Option B	Mass (kg) Option C	Mass (kg) Option D
222	Betongsøyler	Area BTA (above ground)	60	199	25847	22806	25847	25847
222	Stålsøyler (hulprofil)	Area BTA (above ground)	60	2000	25092	22140	25092	25092
223	Betongbjelker	Area BTA (above ground)	60	197	154903	136679	154903	154903
223	Stålbjelker (valseprofil)	Area BTA (above ground)	60	2000	117504	103680	117504	117504
231	Yttervegg av betong	Ext. wall Area (above ground)	60	170	87877	80109	72104	98801
231	Yttervegg av lettklinker	Ext. wall Area (above ground)	60	501	35600	32453	29210	40026
232	Yttervegg av bindingsverk	Ext. wall Area (above ground)	56	506	55364	50470	45427	62247
233	Glassfasade	Ext. wall Area (above ground)	30	2000	8821	8041	7238	9917
234	Trevinduer med alukledning, 3	Ext. wall Area (above ground)	35	2000	40914	37297	33570	46000
234	Ytterdører i stål	Ext. wall Area (above ground)	30	2000	2428	2214	1992	2730
235	Maling utvendig, 0.27 kg/m2	Ext. wall Area (above ground)	10	500	169	154	139	190
235	Teglkledning med mørtel	Ext. wall Area (above ground)	60	1697	159251	145174	130668	179047
235	Trekledning	Ext. wall Area (above ground)	40	500	5218	4757	4281	5867
236	Innvendig puss 3 mm	Ext. wall Area (above ground)	60	500	676	616	555	760
236	Maling innvendig, 0.27 kg/m2	Ext. wall Area (above ground)	10	500	379	345	311	426
241	Innervegg av betong 150 mm	Int. wall Area (above ground)	60	117	57365	50360	46211	56278
241	Innervegg av betong 250 mm	Int. wall Area (above ground)	60	117	23902	20983	19254	23449
241	Innervegg av lettklinker	Int. wall Area (above ground)	60	500	16736	14692	13482	16419
242	Lettvegg med 1-lags gips, 100	Int. wall Area (above ground)	45	680	18825	16527	15165	18469
243	Glass front systemvegg	Int. wall Area (above ground)	60	500	1282	1126	1033	1258
244	Tredører	Int. wall Area (above ground)	40	500	3078	2702	2479	3020
246	Innvendig puss 3 mm	Int. wall Area (above ground)	60	500	1347	1182	1085	1321
246	Maling innvendig, 0.27 kg/m2	Int. wall Area (above ground)	10	500	305	268	245	299
246	Våtromsvinyl	Int. wall Area (above ground)	20	2000	327	287	263	321
251	Betong hulldekke 265 mm	Slab Area (above ground)	60	200	2264400	1998000	2264400	2264400
252	Gulv på grunn	Footprint Area (above ground)	60	146	386157	340727	386157	257438
253	Armert påstøp	Slab Area (above ground)	60	85	747864	659880	747864	747864
253	Avrettingsmasse 20 mm	Slab Area (above ground)	60	500	208129	183643	208129	208129
255	Linoleum	Area BRA (above ground)	20	2000	13219	11664	13219	13219
255	Parkett	Area BRA (above ground)	40	500	3084	2722	3084	3084
255	Vinyl	Area BRA (above ground)	20	2000	2479	2187	2479	2479
256	Malt gipsimling	Area BRA (above ground)	39	500	15367	13559	15367	15367
257	Systemhimling med oppheng	Area BRA (above ground)	60	636	33929	29938	33929	33929
261	Takkonstruksjon hulldekke	Roof Area	60	223	578631	510557	578631	385754
262	Asfalttekking, to lag	Roof Area	20	500	9181	8101	9181	6121
281	Betongtrapp	External wall Height (above grc	60	128	23400	23400	19200	35100

Option A:



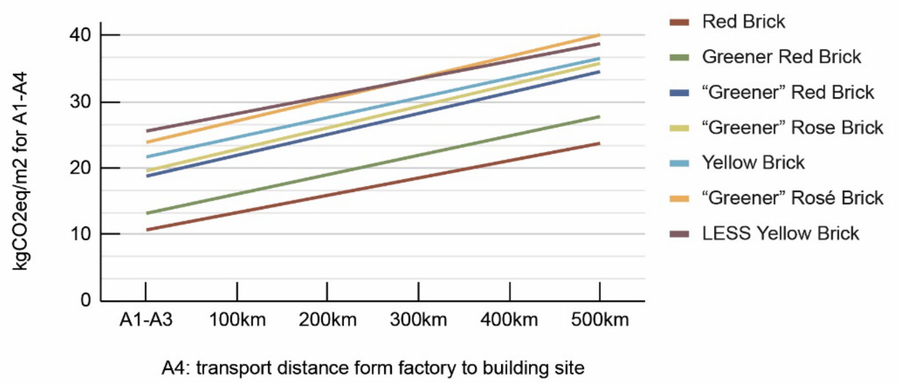


Option B - D give similar graphs which can be seen in the digital appendix.

File name: Appendix 4 - Inventory Automodel Reduzer

Appendix 5: Calculation of transport emissions of bricks

Transport factor		0.1667	kgCO2eq/tkm			
km	0	100	200	300	400	500
	kgCO2eq/m2					
	A1-A3	**100km**	**200km**	**300km**	**400km**	**500km**
Red Brick	11	13	16	19	21	24
Greener Red Brick	13	16	19	22	25	28
"Greener" Red Brick	19	22	25	28	31	35
"Greener" Rose Brick	20	23	26	29	33	36
Yellow Brick	22	25	28	31	34	37
"Greener" Rosé Brick	24	27	30	34	37	40
LESS Yellow Brick	26	28	31	34	36	39
Red Brick	37	40	44	47	50	53
Yellow Brick	40	43	46	49	52	55
Red Brick	45	48	51	54	57	60
Yellow Brick	50	53	56	59	62	65
Yellow Brick	60	63	67	70	73	77



	producer		**kgCO2eq/ m2**	**thiknes in m / m2**	**density kg/m3**
Red Brick	Egernsund Wienerberger		10.7	0.108	1450
Greener Red Brick	Randers Tegl		13.2	0.108	1620
"Greener" Red Brick	Randers Tegl		18.8	0.108	1750
"Greener" Rose Brick	Randers Tegl		19.6	0.108	1800
Yellow Brick	Egernsund Wienerberger		21.7	0.108	1650
"Greener" Rosé Brick	Randers Tegl		23.9	0.108	1800
LESS Yellow Brick	Egernsund Wienerberger		25.6	0.108	1463
Red Brick	Randers Tegl		37.2	0.108	1750
Yellow Brick	Egernsund Wienerberger		40.0	0.108	1712
Red Brick	Branch Assoc.in Germany		44.9	0.115	1530
Yellow Brick	Matzen Tegl		50.1	0.108	1600
Yellow Brick	Randers Tegl		60.1	0.108	1825

Also submitted as a digital appendix.

File name: Appendix 5 - Calculation transport emissions of bricks

Appendix 6: Calculation of CLT and concrete hollow-core slab with NS 3720 and FutureBuilt Zero

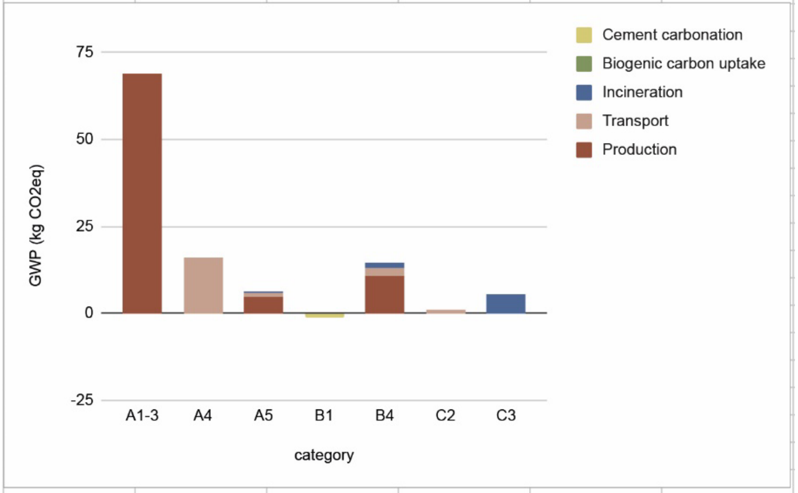
CLT slab with floor build-up: Component in Reduzer

Quantity	Product	Cost [NOK/ unit]	Transport distance [km]	Estimated service life [yrs]	Wastage [%]	Circularity	Mass (A1-3)
0.20 m3	Construction materials → CLT - Cross Laminated Timber Krysslimt tre		500km Standard	60y		☐ Reused ☐ Reusability	84.0 kg
0.050 m3	Floor build-up → Step sound plate, plastic swissporEPS Roll		200km Regional	60y	10%	☐ Reused ☐ Reusability	0.84 kg
0.050 m3	Floor build-up → Screed Avrettingsmasse - typisk verdi		500km Standard	60y	10%	☐ Reused ☐ Reusability	85.0 kg
0.015 m3	Building boards → Plaster, special Gyproc Protect® F – Fireboard		500km Standard	60y	5%	☐ Reused ☐ Reusability	12.4 kg
1.0 m2	Floor → Linoleum Tarkett - Linoleum Flooring 2,5 mm, Veneto, Etrusco, Style Elle, Style Emme, Trentino, Veneto Essenza		2000km Distant	25y	10%	☐ Reused ☐ Reusability	3.0 kg

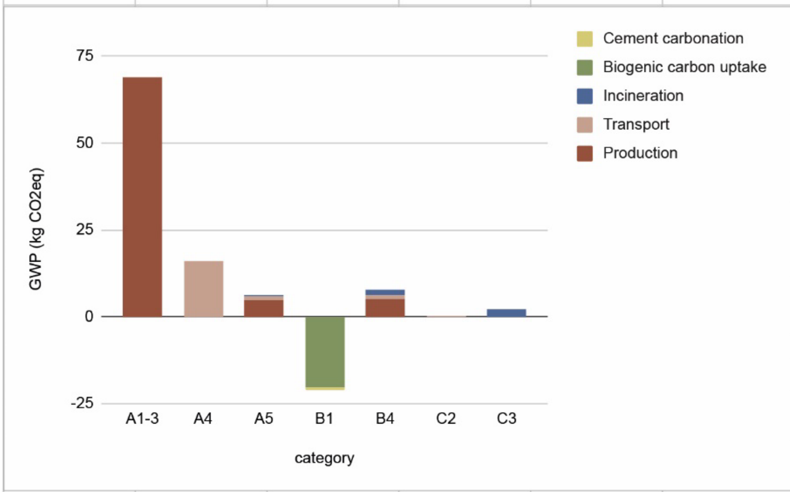
Concrete hollow-core slab with floor build-up: Component in Reduzer

Quantity	Product	Cost [NOK/ unit]	Transport distance [km]	Estimated service life [yrs]	Wastage [%]	Circularity	Mass (A1-3)
0.050 m3	Floor build-up → Screed Avrettingsmasse - typisk verdi		500km Standard	60y	10%	☐ Reused ☐ Reusability	85.0 kg
255 kg	Concrete → Hollow-core slab CONTIGA, Hulldekker Lavkarbonklasse A		50km Local	60y	5%	☐ Reused ☐ Reusability	255 kg
0.015 m3	Building boards → Plaster, special Gyproc Protect® F – Fireboard		500km Standard	60y	5%	☐ Reused ☐ Reusability	12.4 kg
1.0 m2	Floor → Linoleum Tarkett - Linoleum Flooring 2,5 mm, Veneto, Etrusco, Style Elle, Style Emme, Trentino, Veneto Essenza		2000km Distant	25y	10%	☐ Reused ☐ Reusability	3.0 kg
0.050 m3	Floor build-up → Step sound plate, plastic swissporEPS Roll		200km Regional	60y	10%	☐ Reused ☐ Reusability	0.84 kg

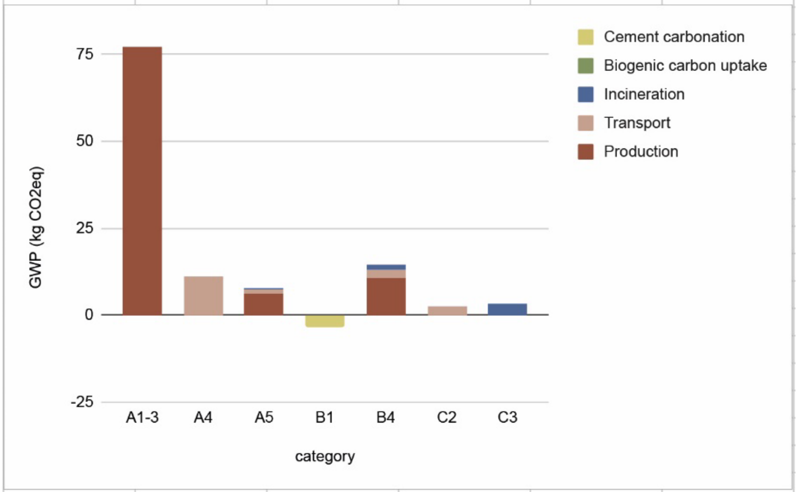
CLT slab with floor build-up (NS 3720)					
	GWP (kg CO2eq)				
category	**Production**	**Transport**	**Incineration**	**Biogenic carbon uptake**	**Cement carbonation**
A1-3	68.79217293	0	0	0	0
A4	0	16.17446144	0	0	0
A5	4.934418647	0.9277635836	0.317088	0	0
B1	0	0	0	0	-1.05825
B4	10.813	2.2484088	1.550208	0	0
C2	0	1.234981114	0	0	0
C3	0	0	5.63712	0	0



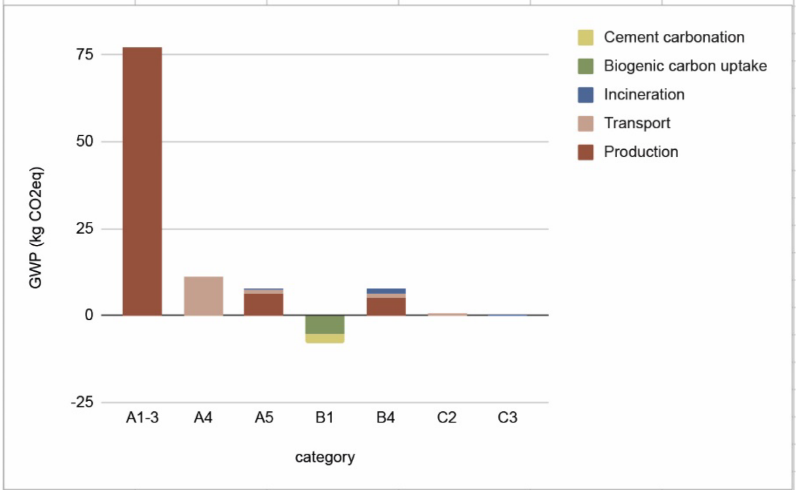
CLT slab with floor build-up (FutureBuilt Zero)					
	GWP (kg CO2eq)				
category	**Production**	**Transport**	**Incineration**	**Biogenic carbon uptake**	**Cement carbonation**
A1-3	68.79217293	0	0	0	0
A4	0	16.17446144	0	0	0
A5	4.934418647	0.9277635836	0.365205858	0	0
B1	0	0	0	-20.32017538	-0.8829901575
B4	5.338761962	1.110119243	1.462199081	0	0
C2	0	0.3281542416	0	0	0
C3	0	0	2.210984809	0	0



Hollow core slab with floor build-up (NS 3720)					
	GWP (kg CO2eq)				
category	**Production**	**Transport**	**Incineration**	**Biogenic carbon uptake**	**Cement carbonation**
A1-3	77.26747293	0	0	0	0
A4	0	11.27696144	0	0	0
A5	6.261183647	1.118605584	0.317088	0	0
B1	0	0	0	0	-3.331371
B4	10.813	2.2484088	1.550208	0	0
C2	0	2.375209114	0	0	0
C3	0	0	3.17088	0	0



Concrete hollow-core slab with floor build-up (FutureBuilt Zero)					
	GWP (kg CO2eq)				
category	**Production**	**Transport**	**Incineration**	**Biogenic carbon uptake**	**Cement carbonation**
A1-3	77.26747293	0	0	0	0
A4	0	11.27696144	0	0	0
A5	6.261183647	1.118605584	0.365205858	0	0
B1	0	0	0	-5.206340665	-2.779653016
B4	5.338761962	1.110119243	1.462199081	0	0
C2	0	0.6311310648	0	0	0
C3	0	0	0.1192051948	0	0



Also submitted as a digital appendix.

File name: Appendix 6 - Calculation CLT and concrete hollow-core slab

NS 3720: *Basis, uten lokalisering 60 år* - Reduzer

Opt. A: 68.0 x 22.5 x 16.8	ⓘ DETAILS EDIT	4 above 0 below	6120 gross (BTA) 5508 usable (BRA) 4957 heated (HBRA) 1530 built-up (BYA)	5129 tonne in 70 inventories DETAILS ⓘ OPEN	2.31e+3 tonne total 377 kg /m²BTA 419 kg /m²BRA 465 kg /m²HBRA
Opt. B: 60.0 x 22.5 x 16.8	ⓘ DETAILS EDIT	4 above 0 below	5400 gross (BTA) 4860 usable (BRA) 4374 heated (HBRA) 1350 built-up (BYA)	4539 tonne in 70 inventories DETAILS ⓘ OPEN	2.05e+3 tonne total 379 kg /m²BTA 421 kg /m²BRA 468 kg /m²HBRA
Opt. C: 68.0 x 22.5 x 14.0	ⓘ DETAILS EDIT	4 above 0 below	6120 gross (BTA) 5508 usable (BRA) 4957 heated (HBRA) 1530 built-up (BYA)	5030 tonne in 70 inventories DETAILS ⓘ OPEN	2.21e+3 tonne total 361 kg /m²BTA 401 kg /m²BRA 446 kg /m²HBRA
Opt. D: 45.3 x 22.5 x 16.8	ⓘ DETAILS EDIT	6 above 0 below	6120 gross (BTA) 5508 usable (BRA) 4957 heated (HBRA) 1020 built-up (BYA)	4863 tonne in 70 inventories DETAILS ⓘ OPEN	2.22e+3 tonne total 363 kg /m²BTA 403 kg /m²BRA 448 kg /m²HBRA

FutureBuilt: *Hovedkriterium 60 år* - Reduzer

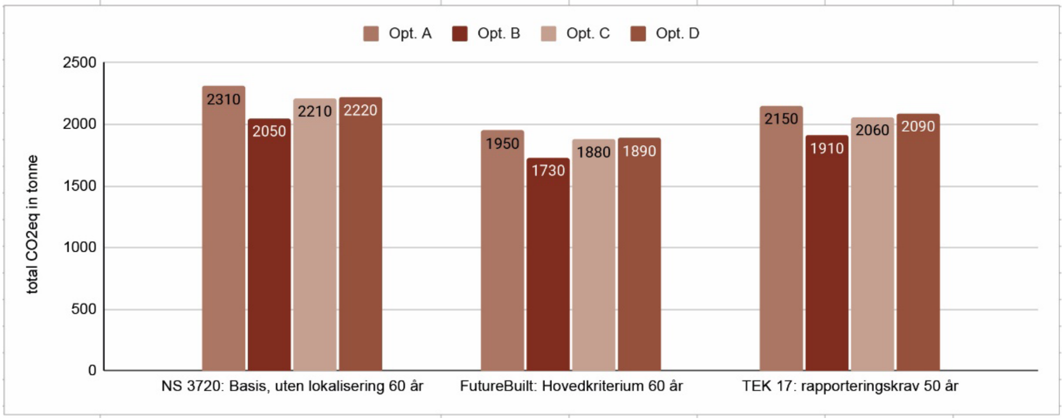
Opt. A: 68.0 x 22.5 x 16.8	ⓘ DETAILS EDIT	4 above 0 below	6120 gross (BTA) 5508 usable (BRA) 4957 heated (HBRA) 1530 built-up (BYA)	5129 tonne in 70 inventories DETAILS ⓘ OPEN	1.95e+3 tonne total 319 kg /m²BTA 354 kg /m²BRA 393 kg /m²HBRA
Opt. B: 60.0 x 22.5 x 16.8	ⓘ DETAILS EDIT	4 above 0 below	5400 gross (BTA) 4860 usable (BRA) 4374 heated (HBRA) 1350 built-up (BYA)	4539 tonne in 70 inventories DETAILS ⓘ OPEN	1.73e+3 tonne total 321 kg /m²BTA 356 kg /m²BRA 396 kg /m²HBRA
Opt. C: 68.0 x 22.5 x 14.0	ⓘ DETAILS EDIT	4 above 0 below	6120 gross (BTA) 5508 usable (BRA) 4957 heated (HBRA) 1530 built-up (BYA)	5030 tonne in 70 inventories DETAILS ⓘ OPEN	1.88e+3 tonne total 307 kg /m²BTA 341 kg /m²BRA 379 kg /m²HBRA
Opt. D: 45.3 x 22.5 x 16.8	ⓘ DETAILS EDIT	6 above 0 below	6120 gross (BTA) 5508 usable (BRA) 4957 heated (HBRA) 1020 built-up (BYA)	4863 tonne in 70 inventories DETAILS ⓘ OPEN	1.89e+3 tonne total 309 kg /m²BTA 343 kg /m²BRA 381 kg /m²HBRA

TEK 17: *rapporteringskrav 50 år* - Reduzer

Opt. A: 68.0 x 22.5 x 16.8	ⓘ DETAILS EDIT	4 above 0 below	6120 gross (BTA) 5508 usable (BRA) 4957 heated (HBRA) 1530 built-up (BYA)	5129 tonne in 70 inventories DETAILS ⓘ OPEN	2.15e+3 tonne total 352 kg /m²BTA 391 kg /m²BRA 434 kg /m²HBRA
Opt. B: 60.0 x 22.5 x 16.8	ⓘ DETAILS EDIT	4 above 0 below	5400 gross (BTA) 4860 usable (BRA) 4374 heated (HBRA) 1350 built-up (BYA)	4539 tonne in 70 inventories DETAILS ⓘ OPEN	1.91e+3 tonne total 354 kg /m²BTA 393 kg /m²BRA 437 kg /m²HBRA
Opt. C: 68.0 x 22.5 x 14.0	ⓘ DETAILS EDIT	4 above 0 below	6120 gross (BTA) 5508 usable (BRA) 4957 heated (HBRA) 1530 built-up (BYA)	5030 tonne in 70 inventories DETAILS ⓘ OPEN	2.06e+3 tonne total 337 kg /m²BTA 374 kg /m²BRA 416 kg /m²HBRA
Opt. D: 45.3 x 22.5 x 16.8	ⓘ DETAILS EDIT	6 above 0 below	6120 gross (BTA) 5508 usable (BRA) 4957 heated (HBRA) 1020 built-up (BYA)	4863 tonne in 70 inventories DETAILS ⓘ OPEN	2.09e+3 tonne total 342 kg /m²BTA 380 kg /m²BRA 422 kg /m²HBRA

total GWP in tonne	Opt. A	Opt. B	Opt. C	Opt. D
NS 3720: Basis, uten lokalisering 60 år	2310	2050	2210	2220
FutureBuilt: Hovedkriterium 60 år	1950	1730	1880	1890
TEK 17: rapporteringskrav 50 år	2150	1910	2060	2090

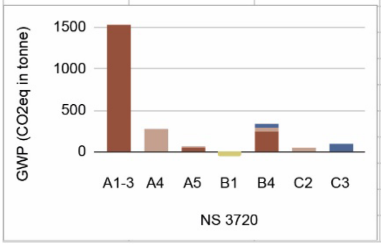
GWP per m2 in kg	Opt. A	Opt. B	Opt. C	Opt. D
NS 3720: Basis, uten lokalisering 60 år	377	379	361	363
FutureBuilt: Hovedkriterium 60 år	319	321	307	309
TEK 17: rapporteringskrav 50 år	352	354	337	342



Also submitted as a digital appendix.

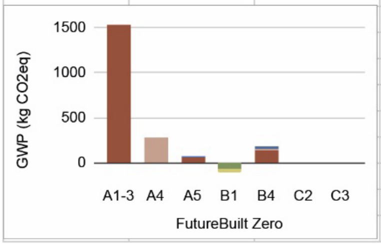
File name: Appendix 7 - Calculation Option A - D total GWP

category	Production	Transport	Incineration	Biogenic carbon uptake	Cement carbonation
A1-3	1530.493907	0	0	0	0
A4	0	278.4330719	0	0	0
A5	53.58000222	10.23120651	7.39370573	0	0
B1	0	0	0	0	-50.6945413
B4	247.7055839	37.55503844	55.41331001	0	0
C2	0	42.75065234	0	0	0
C3	0	0	93.43923487	0	0



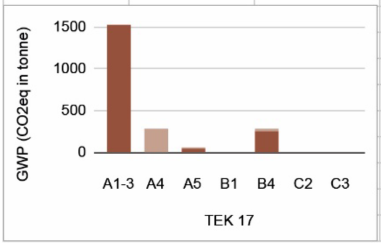
NS 3720

category	Production	Transport	Incineration	Biogenic carbon uptake	Cement carbonation
A1-3	1530.493907	0	0	0	0
A4	0	278.4330719	0	0	0
A5	53.58000222	10.23120651	10.42395412	0	0
B1	0	0	0	-67.45436254	-45.32412024
B4	135.6964764	19.45747679	21.76470245	0	0
C2	0	0	0	0	0
C3	0	0	3.306893973		



FutureBuilt Zero

category	Production	Transport	Incineration	Biogenic carbon uptake	Cement carbonation
A1-3	1526.824787		0	0	0
A4		277.9345583			
A5	53.42556222	10.21252208			
B1					
B4	247.7055839	36.23395011			
C2					
C3					



TEK 17

Also submitted as a digital appendix.

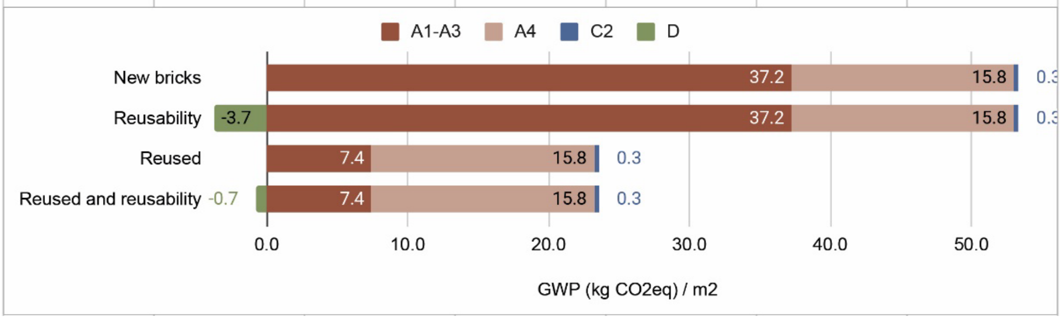
File name: Appendix 8 - Calculation Option A with life cycle stages

Appendix 9: Calculation of brick wall - new, reuse, and reusability with FutureBuilt Zero

Components in Reduzer:

	Description of use	Amount	Composition	Transport distance [km]	Wastage [%]	Mass (A1-3)	Total GWP [CO2e]
(1)	Exterior brick wall - reusability	1.0 m2					49.6 kg
(1)	Exterior brick wall - reused and reusability	1.0 m2		500km		189 kg	22.8 kg
(1)	Exterior brick wall - reused	1.0 m2		500km		189 kg	23.6 kg
(1)	Exterior brick wall - new	1.0 m2		500km		189 kg	53.3 kg

		GWP (kg CO2eq) / m2				
		A1-A3	**A4**	**C2**	**D**	
	New bricks	37.2	15.8	0.3	0.0	
	Reusability	37.2	15.8	0.3	-3.7	
	Reused	7.4	15.8	0.3	0.0	
	Reused and reu	7.4	15.8	0.3	-0.7	



Also submitted as a digital appendix.

File name: Appendix 9 - Calculation brick new, reused and reusability

Appendix 10: Calculation of timber cladding 60 years vs. 30 years with FutureBuilt

ESL of timber cladding 60 years:

235 Outer cladding and surfacing	(2)	timber cladding 60years	1.0 m2		500km	15%	14.1 kg	2.7 kg

Quantity	Product	Cost [NOK/ unit]	Transport distance [km]	Estimated service life [yrs]	Wastage [%]	Circularity	Mass (A1-3)	Total GWP [CO2e]
4.0 m	Construction materials → Construction timber Kobberimpregnert trelast i klasse AB		500km Standard	60y	15%	☐ Reused ☐ Reusability	3.7 kg	0.68 kg
1.0 m2	Cladding → Wood cladding Royalimpregnert trelast		500km Standard	60y	15%	☐ Reused ☐ Reusability	10.5 kg	2.1 kg

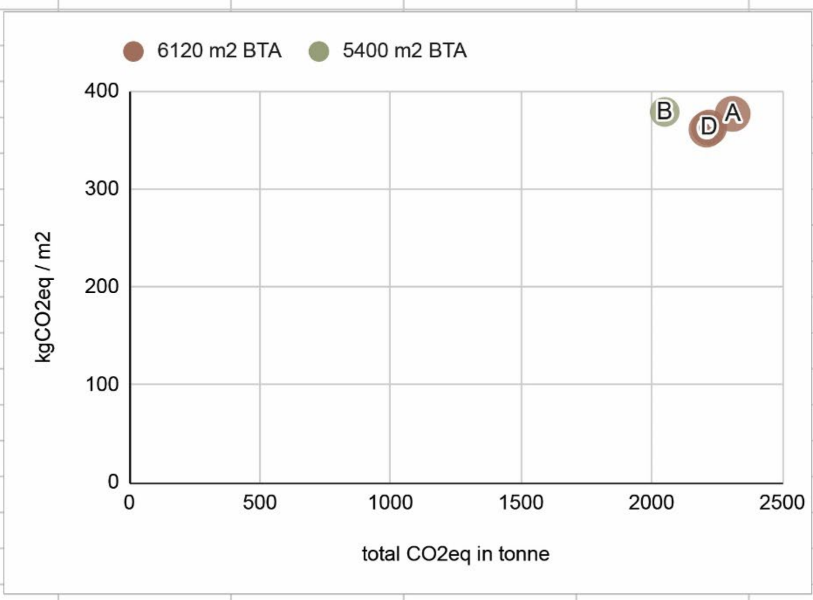
ESL of timber cladding 30 years:

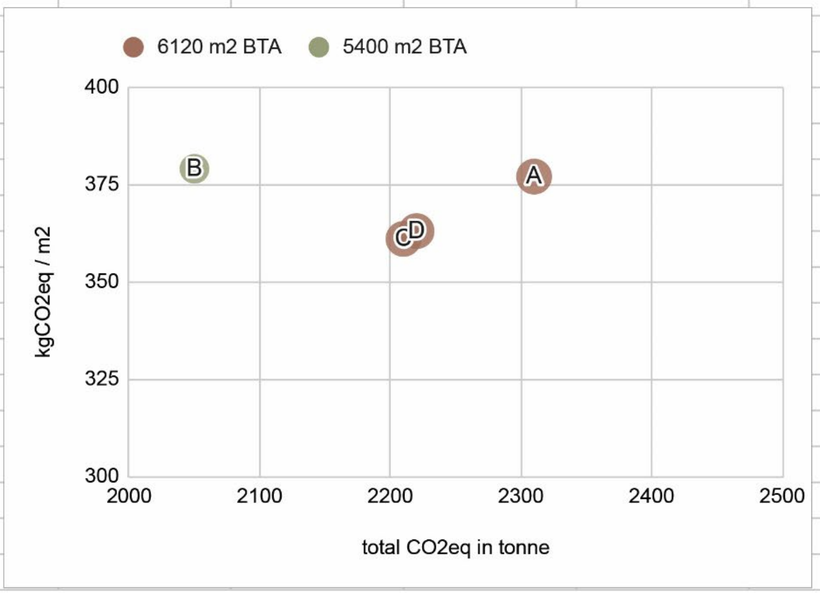
235 Outer cladding and surfacing	(2)	timber cladding 30years	1.0 m2		500km	15%	14.1 kg	5.1 kg

Quantity	Product	Cost [NOK/ unit]	Transport distance [km]	Estimated service life [yrs]	Wastage [%]	Circularity	Mass (A1-3)	Total GWP [CO2e]
1.0 m2	Cladding → Wood cladding Royalimpregnert trelast		500km Standard	30y	15%	☐ Reused ☐ Reusability	10.5 kg	3.8 kg
4.0 m	Construction materials → Construction timber Kobberimpregnert trelast i klasse AB		500km Standard	30y	15%	☐ Reused ☐ Reusability	3.7 kg	1.3 kg

Appendix 11: Calculation of Option A - D for shape optimization with NS 3720

	total CO2 in ton	CO2/m2	BTA		
A	2310	377	6120		68.0 x 22.5 x 16.8 m
B	2050	379	5400		60.0 x 22.5 x 16.8 m
C	2210	361	6120		68.0 x 22.5 x 14.0 m
D	2220	363	6120		45.3 x 22.5 x 16.8 m
NS 3720	basic, without location - 60 years				





Also submitted as a digital appendix.

File name: Appendix 11 - Calculation Option A - D shape optimizati

NTNU

Norwegian University of
Science and Technology