Deriving and mitigating the upfront carbon of a large-scale industrial project

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Acronyms

BoP Balance of Plant 44

CCS Carbon Capture & Storage 23, 62

CCU Carbon Capture & Utilisation 23, 62

CO_2 Carbon Dioxide 1, 4, 7, 65, 66

CO_2e Carbon Dioxide equivalents 3, 7, 12–14, 20, 21, 24, 34, 36, 47, 56, 61–63, 65, 66, 68

EAF Electric Arc Furnace 13, 22, 23, 62

EF Emissions Factor 12–15, 18, 21, 24, 30, 34, 38, 39, 49, 61, 62

EPD Environmental Product Declaration 13, 16, 40, 51, 52, 63, 64

FA Fly Ash 22, 62

GFA Gross Floor Area 15, 16, 55

GGBS Ground Granulated Blast Furnace Slag 22, 62

GHG Green House Gas 7, 20, 21

GWP Global Warming Potential 7, 9, 12, 13, 18, 19, 42

H2GS H2 Green Steel 1, 3, 4, 17, 18, 29, 31, 32, 35, 38, 49, 53–55, 57, 60, 61, 64–67, 69

HVAC heating, ventilation, and air cooling 44, 52

JRC Joint Research Centre 42

LCA Life Cycle Assessment 1, 3, 5, 9, 12, 13, 15–18, 21, 34, 44–46, 48, 49, 51, 52, 58, 59, 65

rebar reinforcement steel bar 13, 23, 32, 42

RFI Request for Information 26

RFP Request for Proposal 26, 27, 39, 40, 48, 63, 64, 66, 68

Sammanfattning

Byggbranschen har länge fokuserat på att öka effektiviteten av den bebyggda miljön och således har också koldioxidutsläppen under driftsfasen av byggnaderna minskat. I takt med att de operativa koldioxidutsläppen har minskat, har andelen utsläpp kopplade till uppförandet av byggnaderna ökat, på engelska kallade embodied och upfront carbon. Under en byggnads livscykel syftar termen upfront carbon på alla de utsläpp som härstammar från utbrytning av råmaterial fram till dess att konstruktionen har uppförts. På senare tid har kunskapen om problemet med upfront carbon ökat, men det finns ett stort behov av att sprida kunskapen ytterligare.

De huvudsakliga fokusområdena i detta examensarbete har varit att definiera metodiken och att beräkna konstruktionsutsläppen (upfront carbon) av H2 Green Steels gröna stålverk som ska byggas i Boden, Sverige. Målet har varit att skapa förståelse och lärdom kring koldioxidutsläppen, samt att undersöka vilka möjligheter det finns att hantera och påverka koldioxidutsläppen från byggnationen.

Innan en detaljerad design är färdigställd, är antagande, tumregler och generiska värden ovärderliga för att ta fram ett värde på koldioxidutsläppen. Avsaknaden av korrekt data borde inte avskräcka från att analysera dessa utsläpp. Det finns en utmärkt möjlighet att reducera utsläppen i ett stadie där val av material och leverantörer ännu inte är avslutade, och där ingenjörsarbete inte är färdigställt. Ju tidigare analysen påbörjas, desto större är potentialen att minska koldioxidutsläppen.

Abstract

For a long time, the construction and building industries have focused on increasing the efficiency of the built environment and reducing the emissions during the operations of buildings. As a consequence of the decreased operational emissions, the share of so-called embodied and upfront carbon has increased. In the life cycle of a building, the upfront carbon is associated with the emissions from the extraction of raw materials up until a building has been erected. Knowledge about the prevalent problem of upfront carbon has increased recently, but there is a dire need to spread the knowledge further.

The focus of this thesis project has been to define the methodology and calculate the upfront carbon of the H2 Green Steel greenfield steel plant that is to be constructed in Boden, Sweden. The aim has been to enable increased knowledge about upfront carbon and how to manage and influence the emissions from construction.

Before the detailed design is finished, assumptions, rules of thumb, and generic values are invaluable to derive the upfront carbon. The lack of valid data should not deter from assessing the emissions. There is an excellent upfront carbon reduction potential with materials and suppliers yet to be selected and engineering not commenced. The earlier the measurement begins, the greater the reduction potential is.

Acknowledgements

First and foremost, a huge thank you to H2 Green Steel for offering us the privilege to write our thesis with you. To everyone in the H2 Green Steel (H2GS) family that has been involved in helping us one way or another, we are truly grateful. Specifically, we would like to emphasise the exceptional support Nils Marnfeldt, Lars Lundström, and Peter Roberts has given us. The three of you have put new standards for what supervisors are capable of doing. With an everlasting interest and willingness to help in any situation during the course of this project, we cannot think of a better-executed project from your side.

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Finally, we would like to thank everyone who participated in interviews and spent time helping us with this project, especially Alexander Landborn, for helping us on multiple occasions.

Chapter 1.

Introduction

An effective way of assessing the environmental impact of an object of material existence is to conduct a Life Cycle Assessment (LCA). In a complete LCA one can analyse the contribution to the interdependent environmental impact from all life cycle stages. This methodology enables a holistic view where avoidance of sub optimisation is assured. The structure of a LCA is fixed and must follow the international standards ISO 14040 (Muralikrishna and Manickam, 2017). In the cases of construction projects, there are specific standards, most notably EN 15978:2011 titled "Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method". The standard provides calculation rules for the assessment of the environmental performance of new and existing buildings (*Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method* 2011). According to the standard, the object of assessment is the building and its site. Both ISO 14040 and EN 15978:2011 provide toolkits to perform quantitative analysis that can be used to identify hotspots, the overall environmental load and comparison between different choices. These standards enable the possibility to measure, manage, influence and learn about the carbon footprint.

H2 Green Steel (H2GS) is building a large-scale industrial site with multiple facilities and production halls with advanced process equipment together with auxiliary systems. Furthermore, the site requires internal infrastructure and will be equipped with a range of material handling equipment. The typical way of assessing the environmental impact of a construction project is to study the buildings and the earthworks entailed by constructing that building. However, in this case, there is an extensive amount of material needed for the production site to function. Because of this, it makes sense to assess the environmental impact from all the constituents of the functioning industrial site, i.e., more than just the buildings themselves.

Today, the buildings sector, directly and indirectly, accounts for 37% of all global energy-related Carbon Dioxide (CO_2) emissions. Ten of those percentage points are represented by the manufacturing of construction materials, and the remaining part originates from the operational energy in the buildings (IEA, 2021).While organisations such as WorldGBC and World Business Council for Sustainable Development have emphasised increased building efficiency and reduced operational energy emissions for years, the lacking environmental performance of construction has become imminent. Much work has been put into the matter, and the energy efficiency in buildings has improved over time. However, as the relative operational carbon has been reduced, the fraction of embodied carbon in the whole life carbon of buildings has increased, as illustrated in figure 1.1 (Pasanen et al., 2021). There is a need to enhance stakeholders' interest, knowledge and understanding regarding construction-related emissions to halt global warming.

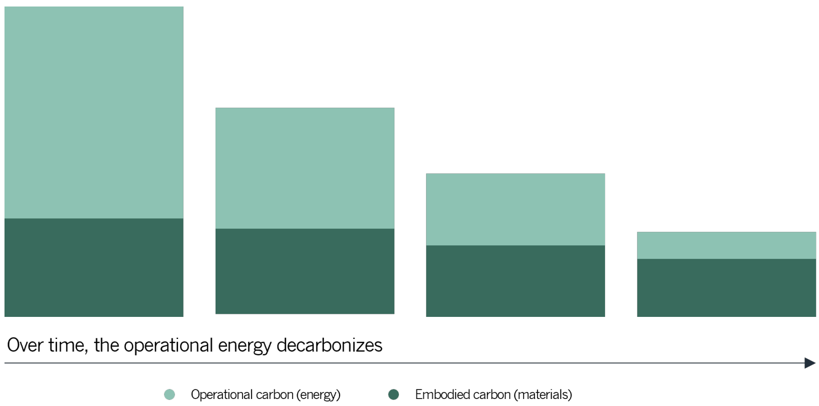


Figure 1.1.: The decrease of operational carbon in relation to embodied carbon over time, figure inspired by Pasanen et al. (2021)

1.1. Problem Statement

It would be convenient to wait with any quantifications of the environmental impact of a construction until the project is finished since that would enable access to exact material quantities and machine hours operated. However, to put the results to actual use, the environmental impact of a construction project should be determined as early as possible. An early assessment allows abatement by identifying hotspots and alternative ways of executing the project.

Studies on upfront carbon for residential-, office-, retail- and educational buildings, among others, are available, including benchmark figures and conclusions on how to decarbonise. For industrial buildings, however, available research and benchmarks are minimal. The industrial buildings are often equipped with heavy process equipment that puts high demands on the substructures. Apart from the buildings themselves, process equipment, auxiliary systems, internal infrastructure and material handling equipment, among others, are also sources of upfront carbon. Moreover, an industrial site can consist of multiple buildings for different production steps, storage and utilities.

Large industrial projects may give rise to significant levels of upfront carbon. There is a need for further research on how to determine the upfront carbon of such a project, not only for the buildings on site but also for the broader range of systems and equipment.

1.2. Research Questions

The research and target of the thesis are based on five research questions:

- Q1. What are the potential Carbon Dioxide equivalents (CO_2e) emissions during the construction of the H2GS large-scale industrial project in Boden, including the construction process, construction material and process equipment?
- Q2. How can a plug- & play model, allowing comparisons of CO_2e construction emissions for a hydrogen plant depending on the equipment used and size of equipment, be implemented?
- Q3. What are recommend materials & best practices H2GS can apply to decrease CO_2e emissions?
- Q4. How should suppliers be evaluated and compared based on their CO_2e emissions?
- Q5. What is the downstream value of assessing the carbon footprint from a construction project?

1.3. Contribution

This thesis contributes to knowledge on defining, modelling, and reducing the upfront carbon of a large-scale industrial project. By quantifying the upfront carbon of all transactions connected to the construction of a large-scale industrial site, the carbon footprint can be calculated as a second currency, in addition to money. Rather than just considering the upfront carbon of the buildings on the site themselves, the thesis takes on a holistic view by including the process equipment, auxiliary systems and internal roads, among other things as well. Because of this, the results differ from those in a complete LCA and programs solely calculating the impact of buildings. With knowledge of the potential carbon footprint, the thesis will provide strategies to mitigate the upfront carbon.

Moreover, the thesis also contributes with experience on how a model can be made to identify the carbon footprint of large-scale industrial projects in an early stage, based on scaling mechanics.

Lastly, the thesis explores the potential additional value an assessment of this kind brings to downstream stakeholders such as customers and authorities.

1.4. Distribution of Work

The work has been divided equally between the two authors throughout the project. While most subjects have been discussed and developed together, the day-to-day work has been split to enhance productivity.

To the general model with calculations for the whole H2GS Boden project, the workforce has been split equally. While Hugo Jennehov generally has put more effort into creating the scalable plug- & play model, Nils Olofsson has focused on modelling the Monte Carlo simulations.

1.5. Outline

Chapter 2 includes background and descriptions of theoretical concepts needed to explore the relevant areas of the thesis further. The central term upfront carbon is presented together with a background and related topics. Followed by this, chapter 3 presents the method used to answer the five research questions stated in section 1.2. The results are then presented in chapter 4 which reflects the actual outcome from the method previously presented. In chapter 5 the findings are discussed and compared to benchmarks which are then concluded in chapter 6, conclusions. Finally, suggested future work is presented in chapter 7.

1.6. Company description

Today the European steel industry accounts for 25 per cent of the total European industrial carbon dioxide emissions. Looking at heavy industries globally, the steel and iron sector is the most significant contributor to CO_2 emissions. Addressing the emissions entailing steel production would genuinely make a difference.

H2 Green Steel was founded in 2020 to light-house the transition to green steel production by building a greenfield green steel factory in northern Sweden. As the company matured, H2 Green Steel transitioned from being a steel company to a large-scale, hydrogen-based, and digital native company with the purpose to decarbonise hard to abate industries. By 2025 H2 Green Steel will start the production of its first factory, a green steel plant in Boden. This will be ramped up until 2030 when the plant will produce five million tonnes of fossil-free steel per annum.

Chapter 2.

Theory

The theory section serves the purpose of giving the reader a proper theoretical understanding of the different carbon footprint concepts such as upfront carbon and embodied carbon, how an LCA is conducted and what a climate declaration is. Moreover, the section will give background to how the upfront carbon of the process equipment can be integrated with the upfront carbon of the buildings. Furthermore, theoretical concepts of how uncertainties that arise in calculations of this kind can be tackled are presented. This is followed by a segment where strategies of how the upfront carbon can be mitigated are introduced. Lastly, a small excerpt from the procurement process regarding the supplier selection process is explained.

2.1. Environmental performance of buildings

As established in the European standard EN 15978:2011, the environmental performance of a building can be measured and evaluated based on a life cycle approach. For a complete life cycle assessment of construction, the system boundary includes all life cycle stages of a building as illustrated in figure 2.1.

The complete life cycle assessment includes everything from acquiring the raw materials for the building to their disposal. Depending on the lifetime, the materials can be disposed of during or at the end of the life cycle. The life cycle assessment consists of several stages with sub-modules. Modules A1 to C4 include the environmental impact within the system boundaries, and module D accounts for all components or materials that could be resources for future use. Module D includes the reuse of components together with recycling and energy recovery from materials.

As illustrated in figure 2.1 the stages of a life cycle assessment of a construction with its submodules are

- The Product Stage (Modules A1 to A3)
- The Construction Process Stage (Modules A4 and A5)

- The Use Stage (Modules B1-B7)
- The End-of-Life Stage (Modules C1-C4)
- The Benefits and Loads Beyond the System Boundary (D)

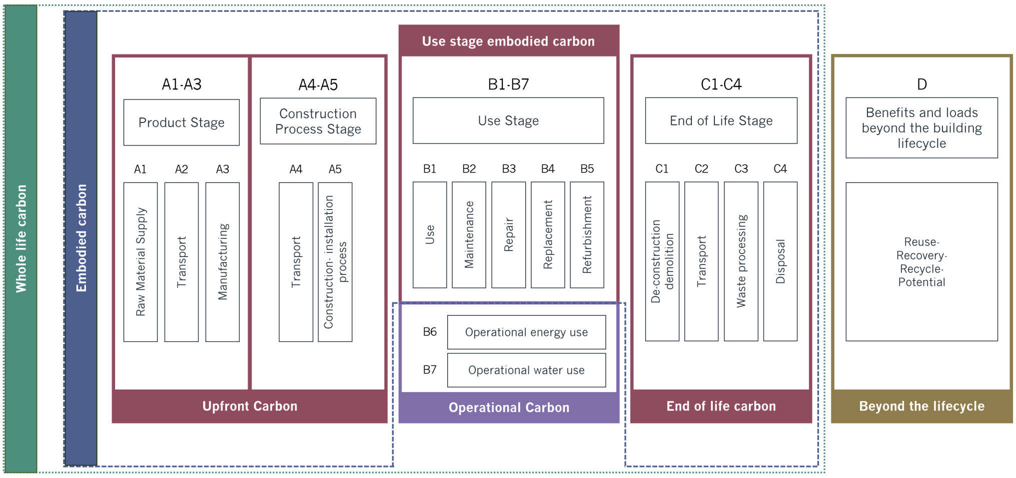


Figure 2.1.: The stages of a life cycle assessment, figure inspired by World Green Building Council (2019)

The environmental impact for each stage or module can be calculated as prescribed in EN 15978:2011, and the type of data used in the calculations will reflect the level of confidence in the results. Different types of data are suitable for different stages of the building project. Different data sets can be used depending on the objective and intended use of the results. Table 2.1 represents the different types of data that can be used in the different stages of the assessment according to EN 15978:2011 (*Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method* 2011).

Table 2.1.: Preferred usage of data depending on point of time of the assessment (*Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method* 2011)

Preferred data	Point of time of the assessment				
	Inception/ Concept design	Detailed design	Construction	Use stage	End of life of the building
Generic data	X	X	X	X	X
Aggregated data	X	X			
Average data	X	X	X	X	X
Product collective data	O	X	X	X	X
Product average data	O	X	X	X	X
Product specific data	O	X	X	X	X
Model scenarios for use stage	X	X	X	X	
Measured data			X	X	X
Other data	O	O	O	O	O
Note: Cross represents the preferred use of data Circle represents alternative sources if available					

The assessment should be made based on the availability of data when the assessment is being performed. In the earliest stage of the building project, the inception/concept design, there is no bill of materials, and the exact materials used are yet to be decided. The lacking knowledge means that generic, aggregated, and average data may be used instead. However, as mentioned, this influences confidence in the results.

2.1.1. The categorisation of carbon emissions

In figure 2.1 several different types of carbon emissions are shown in bold. Those carbon emissions refer to emissions caused by all the Green House Gas (GHG) during the lifetime of a construction or building. All GHGs have a certain Global Warming Potential (GWP) described as the amount of CO_2 which would have the equivalent global warming impact. As an example, CH_4 has a GWP of 25 meaning that 1 kg of emitted CH_4 would be equivalent to emitting 25 kg of CO_2 or in other words, 25 kgCO_2e/kg (Matthew Brander, 2012).

Furthermore, the carbon emissions are divided into different sections. The categorising of carbon emissions is not a clear definition but rather terminology often used in research and reports on the environmental impact of buildings. The categorisation starts with the whole-life carbon that includes stages A1-C4. Within the whole-life carbon, there are multiple subcategories. Below, the embodied and upfront carbon is described in detail. In Appendix C, further information on the remaining categories can be found.

Embodied carbon

The embodied carbon is the carbon emissions entailed from the materials used in the construction and the construction processes throughout the life cycle. That means the embodied carbon covers raw material supply (A1), transportation to the manufacturer (A2), the manufacturing process (A3), transportation to the construction site (A4), the construction installation process (A5), use phase (e.g., the release of substances from the façade, according to *Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method* (2011)) (B1), maintenance (B2), repair (B3), replacement (B4), refurbishment (B5), deconstruction (C1), transport to the end-of-life destinations (C2), the waste processing (C3) and disposal (C4). Note that benefits and loads beyond the building life cycle are reported separately and that the operational carbon (B6-B7) is not included in the embodied carbon (World Green Building Council, 2019). In other terms, embodied carbon represents the carbon emissions from the cradle to the grave.

Figure 2.2 demonstrates typical distributions of embodied carbon based on 1000 European buildings. For all types of buildings, concrete and steel make up more than 60 per cent of all embodied carbon; as for industrial buildings, the corresponding figure is more than 80 per cent (One Click LCA, 2021a).

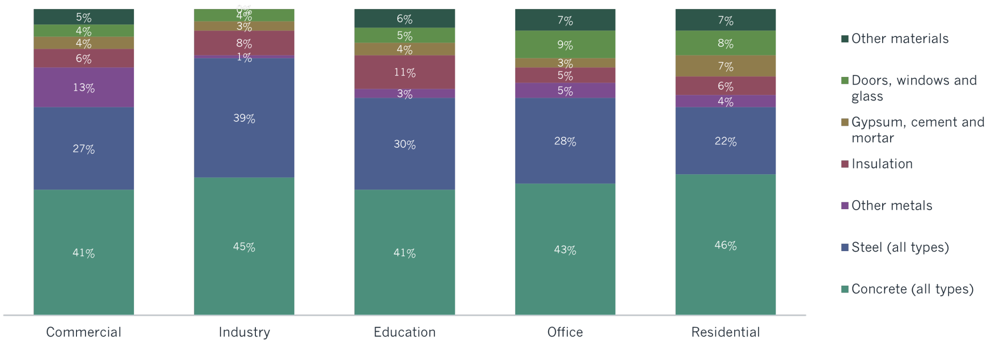


Figure 2.2.: Benchmarks for embodied carbon data per building material and building type, figure inspired by One Click LCA (2021a)

Upfront carbon

The upfront carbon is part of the embodied carbon but only refers to the carbon emissions entailed from the product and construction process stages of the LCA. That means the upfront carbon covers LCA modules A1-A5. In other terms, upfront carbon represents the carbon emissions from cradle to practical completion (Gibbons and Orr, 2020). The upfront carbon is the carbon emissions that are generated before the building is used, meaning that upfront carbon is carbon emissions that have already been released to the atmosphere when operations commence (World Green Building Council, 2019). In a report by ARUP and wbcsd (2021), six case studies on the whole-life carbon of residential buildings are presented and discussed. For these buildings, it was concluded that the upfront carbon represents around 30% of the whole-life carbon, thus it is vital to increase knowledge and to decrease emissions associated with upfront carbon. Furthermore, modules A1-A5 are important because the emissions will be released before 2050, making them critical to mitigating to reach the 1.5-degree target (Gibbons and Orr, 2020).

2.1.2. Assessing the upfront carbon in early design stages

The focus of this section will be on upfront carbon, LCA modules A1-A5. As previously mentioned, mitigating the upfront carbon is critical to reaching the 1.5-degree target. Moreover, since A1-A5 emissions usually represent a large part of the embodied carbon, the emissions make up for a significant carbon reduction potential (Gibbons and Orr, 2020).

A large portion of the upfront carbon descends from the material quantities and their respective GWP value. Therefore, it can be challenging to assess the upfront carbon accurately in the early stages of a construction project, e.g., in the concept stage, where no quantities are set. However, the challenges should not be a deterrent for commencing calculations early in projects. As figure 2.3 shows, calculations become more accurate the longer the project has come. Therefore, updates should be made to early assumptions as more precise information becomes available.

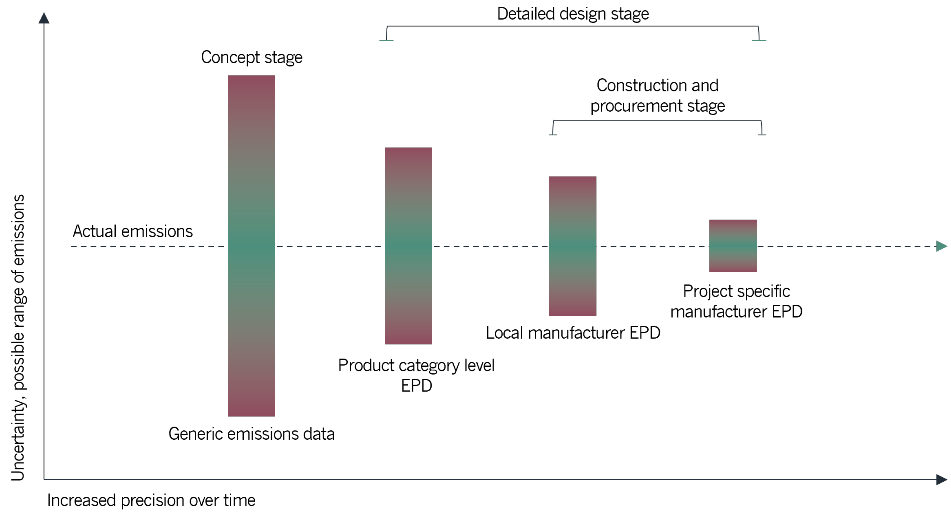


Figure 2.3.: The increased precision of calculations depending on data available, figure inspired by One Click LCA (2021b)

Figure 2.4 gives a more detailed look into why commencing upfront carbon calculations at an early stage is desirable to obtain higher carbon savings. As the project progresses, more and more construction variables are set, limiting the potential to reduce embodied carbon. One way to do so is to consider upfront carbon as one of the critical success factors (Pomponi, De Wolf and Moncaster, 2018). Studying figure 2.5 it can be seen that addressing the upfront carbon of a construction project at an early stage yields a higher carbon reduction potential. For example, if calculations are begun in the concept stage, there are advantages such as high flexibility in changing contractors and materials, enabling a more considerable carbon saving potential. There is also the possibility of finding major carbon hotspots and assigning targets for maximum total building impact. However, in a more detailed design stage where BIM-models might be available, there is a possibility to compare designs and optimise these (One Click LCA, 2021b).

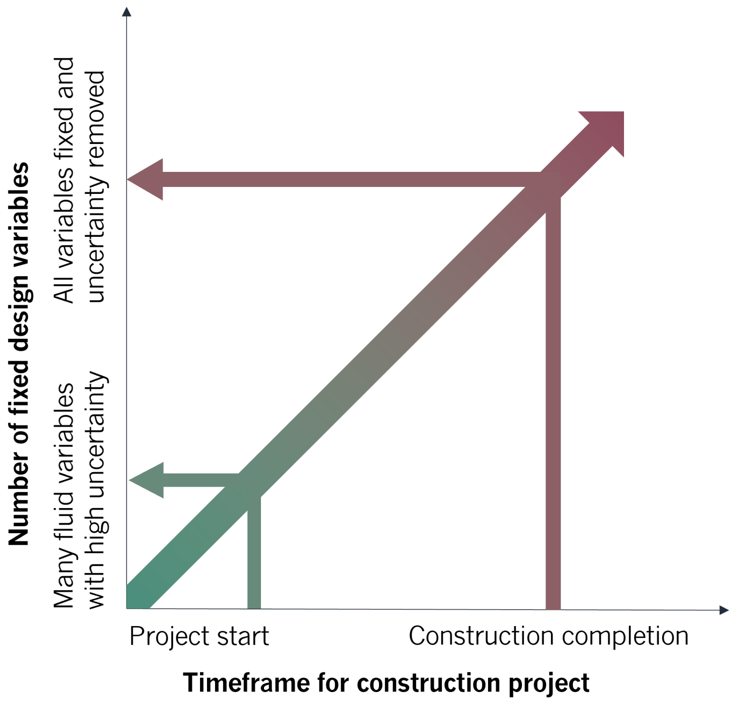


Figure 2.4.: Flexibility decreases as the project develops, figure inspired by Pomponi, De Wolf and Moncaster (2018)

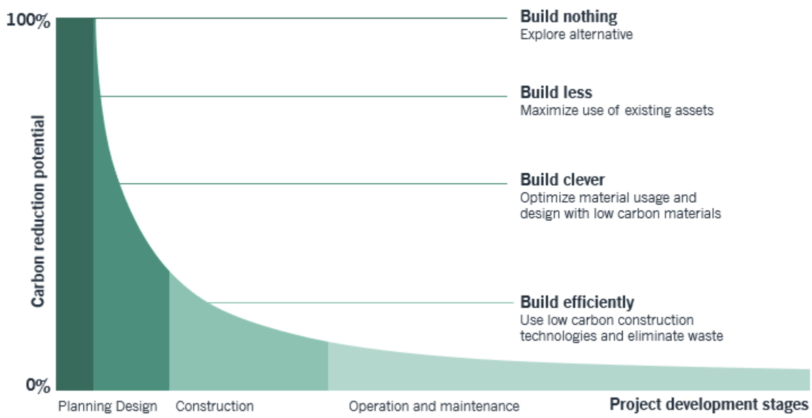


Figure 2.5.: Carbon reduction potential decreases as the project develops, figure inspired by One Click LCA (2021b)

2.2. Calculating the upfront carbon

One basis of analysis on any environmental load is quantification. This section introduces the theory connected to the methodology of calculating the upfront carbon. The formulas used to calculate the different LCA modules A1-A5 are presented. Furthermore, the variables needed for the formulas are explained.

2.2.1. LCA Modules A1-A3 - Product stage

The product stage containing modules A1-A3 represents most of the upfront carbon in modules A1-A5 and the total embodied carbon. The GWP data for the modules A1-A3 are in most cases lumped together and reported as one Emissions Factor (EF) (LETI, 2020). To calculate the embodied carbon from modules A1-A3, the material quantities in the construction project are multiplied with the respective EF according to equation 2.2. The embodied carbon for each material is then summed to calculate the total product stage embodied carbon, according to equation 2.1. The unit used for the quantity is often $kgCO_2e$.

$$EC_{A1-A3} = \sum_i EC_{A1-A3,i} \tag{2.1}$$

$$EC_{A1-A3,i} = \sum_i (Q_i \cdot EF_i) \tag{2.2}$$

Where

EC_{A1-A3} = The total product stage, A1-A3, embodied carbon
$EC_{A1-A3,i}$ = The product stage, A1-A3, embodied carbon for the *i*th material
Q_i = Quantity of the *i*th material
EF_i = The emissions factor for the *i*th material (Gibbons and Orr, 2020)

Material quantities

In the concept stage of a project, material quantities can be acquired from cost estimations, assumptions of material quantities, or early design tools. As the project proceeds, specifications on quantities of materials used in the project will be elaborated, thus increasing the calculations' level of detail. Even though the estimated quantities of the materials used while in the concept stage can differ noticeably from the quantities used in the finished project, starting at an early stage can help identify the materials that have a significant impact on the total embodied carbon.

Emissions factors

The EF data for the materials in the product stage can be of a large variety for the same material. The factors depend on multiple variables such as where the product is produced, the material composition and the production method. Steel illustrates the range of carbon factors well. Comparing an Environmental Product Declaration (EPD) of reinforcement steel produced by CELSA Nordic in Sweden with a similar product produced by Pacific Steel in New Zealand, the differences in GWP are significant. CELSA Nordic produces one type of reinforcement steel bar (rebar) from hot-rolled long steel products made from scrap in an Electric Arc Furnace (EAF) with an emission factor of 0.373 $kgCO_2e/kg$ rebar (Celsa Steel Service AB, 2021). Pacific steel produces a similar type of rebar with a recycled content of 5% together with steel billets from New Zealand Steel. This type of rebar has an emission factor of 3.78 $kgCO_2e/kg$ rebar (Pacific Steel, 2018).

There are different types of GWP data available. An EPD such as the ones used in the example on different types of rebar are documents that show manufacturer-specific data on the environmental impact of a product. EPD International AB who is responsible of the International EPD® System describes an EPD accordingly:

> *"An Environmental Product Declaration (EPD) is an independently verified and registered document that communicates transparent and comparable information about the life-cycle environmental impact of products in a credible way* (The International EPD System, 2021)."

In the early stages of the construction project, information on where materials will be sourced may be limited. In that case, generic data can be used until more information is obtained. However, it is important to be transparent on any assumptions made and update the carbon factors when possible. Depending on the understanding of the sourcing, generic data can be based on local, regional, national or even international averages (Gibbons and Orr, 2020).

2.2.2. LCA Module A4 - Transportation

Module A4 is part of the construction phase in a construction LCA, concerning transport from the gates of the production location to the construction site. In addition, the module accounts for the upfront carbon entailed by transporting the equipment used on the construction site to and from the site. A4 is one of the less extensive modules in an LCA (Gibbons and Orr, 2020). While there is a lack of data on the upfront carbon for industrial buildings, there are plenty of benchmarking studies on residential buildings.

A4 is normally accounting for less than 2 percent of the whole-life carbon (One Click LCA, 2021b; LETI, 2020).

Depending on where the materials are sourced from, the transport will vary. For longer transport distances, multiple modes of transportation are common, which is important to consider when calculating the upfront carbon. The embodied carbon from the transport stage can be calculated according to:

$$EC_{A4} = \sum_{i} EC_{A4,i} \tag{2.3}$$

$$EC_{A4,i} = \sum_{i} (W_i \cdot EF_{A4,i}) \tag{2.4}$$

$$EF_{A4,i} = \sum_{Mode} (TD_{Mode} \cdot TEF_{Mode}) \tag{2.5}$$

Where

EC_{A4} = The total EC from transporting all construction materials to the site
$EC_{A4,i}$ = The EC from transporting the *i*th material to the site
W_i = Weight of the *i*th material
$EF_{A4,i}$ = The emission factor for transporting the *i*th material to the site
TD_{Mode} = Transport distance for each transport mode
TEF_{Mode} = Transport emission factor for each transport mode. Usually found in e.g., kgCO_2e/t&km (Gibbons and Orr, 2020)

In the early stages of a project, the variables for calculating the EC_{A4} can be of high uncertainty. The transport modes and distances travelled will not be sure until the project is completed. However, in the early stages of the project, the EC_{A4} can be estimated using generic data of transport emissions for different modes as well as distances. While this way of working does not result in the exact footprint figure, it can be used to identify significant sources of upfront carbon, enabling a considerable carbon reduction potential. As the project succeeds, the data will be improved, and the calculations can be refined (Gibbons and Orr, 2020). While calculating the $EF_{A4,i}$ the return trips for the respective mode of transport should be taken into account if they do not serve a purpose for other uses.

2.2.3. LCA Module A5 - Construction installation process

The carbon emissions related to LCA module A5 are called construction installation process emissions and usually represent a rather small part of the total life cycle carbon emissions. However, since this number can be higher for heavy civil works, it should not be neglected (Gibbons and Orr, 2020). The construction installation process emissions include waste-related emissions, hereon called A5w emissions, and construction activity related emissions, A5a emissions. All in all, A5 emissions include all types of energy used on-site and all waste generated throughout the construction process (RICS, 2017). Equation 2.6 illustrates how the total construction site EC_{A5} is derived, while equations 2.7-2.8 describe how the waste contributions are calculated. For the total energy use, A5a, One Click LCA has two scenarios for typical energy use on Nordic construction sites available, one for the fuel use and one for the electricity use. Both of these scenarios are measured in relation to m^2 Gross Floor Area (GFA) as shown in equation 2.9.

$$EC_{A5} = EC_{A5w} + EC_{A5a} \tag{2.6}$$

$$EC_{A5w} = \sum_i EC_{A5w,i} \tag{2.7}$$

$$EC_{A5w,i} = WF_i \cdot Q_i \cdot (EF_{A1-A3,i} + EF_{A4,i}) \tag{2.8}$$

$$\begin{aligned} EC_{A5a} = &\left[\left(\frac{\text{Fuel usage}}{\text{m}^2}\right) \cdot (\text{m}^2\ \text{GFA}) \cdot (EF_{\text{Diesel}})\right] \\ &+ \left[\left(\frac{\text{Electricity usage}}{\text{m}^2}\right) \cdot (\text{m}^2\ \text{GFA}) \cdot (EF_{\text{Electricity}})\right] \end{aligned} \tag{2.9}$$

Where

EC_{A5} = Total construction and installation, A5, emissions for the entire construction site
$EC_{A5w,i}$ = Constuction waste embodied carbon for the ith material
WF_i = Waste factor for the ith material, % of total delivered weight
$EF_{A13,i}$ = Modules A1-A3 emissions factor
$EF_{A4,i}$ = Emissions factor for transportation to the construction site, calculated in the same way as in equation 2.5

Waste related emissions, A5w

The view on how to calculate emissions occurring due to waste varies. Certain sources such as Gibbons and Orr (2020) mean that even more parameters than those accounted for in equation 2.8 above should be included. Gibbons and Orr (2020) state that parameters from the LCA end of life modules, C2 (transport away from construction site) and C3-C4 (waste processing and handling), also should be included in A5w. Meanwhile, the National Board of Housing, Building and Planning (Sv. Boverket) only includes the emissions occurring due to manufacturing the wasted materials and transporting them to the construction site (Boverket, 2021c), meaning the A1-A3 and A4 emissions. One thing that both sources have in common is the waste factor, which is to be multiplied by the A1-A3 emissions factor and the A4 emissions factor. Waste factors for various construction materials and elements can be found either in the "*Climate Database*" provided by the National Board of Housing, Building and Planning (Boverket, 2021a) or from EPDs if available. However, using the data found in an EPD for module A5 emission calculations should be done carefully. Data from EPDs must be cross-referenced against construction practices used for the specific project. If the practices used on-site agree with those stated in the used EPD, then the data can be used (RICS, 2017).

Site activity related emissions, A5a

Emissions related to on-site construction activities include electricity- and fuel use, e.g., machinery or diesel generators. In the early stages of a construction project, such figures can be challenging to come by or estimate. However, until actual data collection has been initiated, scenarios or standard numbers based on previous projects can be used. As previously stated, One Click LCA provides two reference scenarios that can be used early on in projects to enable A5a calculations. The scenarios as mentioned earlier relate emissions to GFA, with the following values:

$$\text{Diesel usage factor} = 5.2\ \text{l/m}^2$$
$$\text{Electricity usage factor} = 43\ \text{kWh/m}^2$$

While this necessarily does not give a correct picture of the actual outcome on the construction site, it can be a basis for analysis that can reduce the A5 emissions. Furthermore, the contractor needs to collect energy use data during construction. The collected data should be used to update the assumptions and be used as benchmarks in other projects.

2.3. Climate declaration

By the 1st of January 2022, new regulations from the National Board of Housing, Building and Planning took effect. The introduction of climate declaration serves the purpose of minimising the impact of new construction and affects all new buildings applying for a building permit after the introduction date (Boverket, 2021e). However, certain building types, such as industrial buildings, have been exempted from the law of climate declarations (Boverket, 2021b). The scope of a climate declaration includes impacts from the LCA modules A1-A5 only (Boverket, 2021d), however not all materials and equipment are to be accounted for. What is to be included and excluded in a climate declaration is summarised in table 2.2

Table 2.2.: Construction elements excluded from climate declarations (Boverket, 2022b)

Construction element	Included	Excluded
Load-bearing structural parts - Foundation	Slab on ground, soles, reinforcement beams, foundation walls and insulation under ground	Piles and other stabilisation measures such as retaining walls
Load-bearing structural parts - Other	Frame (beam, floor, pillars, wall), wall to ground, domestic roof construction, castings, stairs, ramps and balconies	Balconies and verandas not part of the climate screen or load-bearing structure
Climate screen	Exterior wall up until building board, roofs and floors, integrated solar cells, facade cladding, plaster and painting on exterior wall, windows, exterior doors	Internal surface layers, roof safety and rainwater systems, putty on interior walls, facade blinds and sun protection, facade ladders and external fire stairs
Interior walls	Interior walls up until building board, glass sections, interior doors, suspended subfloor, suspended ceiling, interior ceiling	Internal surface layers (putty, paint, wallpaper), ceiling and floor moldings, window sills, interior surfaces (parquet floors, linoleum carpet,tiles)

2.4. Widening the scope

The object of assessment in the standard EN 15978:2011 is the building and its site (*Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method* 2011). In this case, where an industrial site is being built, there are an extensive amount of materials needed for the production site to function. Because of this, H2GS would like to understand what carbon footprint this will entail, apart from only the buildings themselves. This view enables the possibility to affect and learn about the carbon footprint from these parts as well. The process equipment, auxiliary systems, internal infrastructure and material handling equipment, among others, are all products. Those products have upfront carbon associated with them, just like the built environment. To properly do this analysis, every item should be assessed according to an LCA. However, to conduct an LCA for every item going into the construction site is not realistic in regards to available data and time at this point.

Instead, to include these products, the same methodology used to calculate the up-front carbon of a building was applied. This means modules A1-A5 for each product beyond the building materials were included. Ideally, this would be accomplished by including everything from raw material extraction, transport to the production facility, and energy use during assembly for each item. Considering that a product in most cases consists of several different materials, this process would have to be repeated for each material. Then, modules A4 and A5 would need to be accounted for as well, meaning the transport to the H2GS site together with potential waste and energy usage on site. However, due to the early design stage, a lot is still to be decided. This means that the ideal way of including those items is not a realistic approach. Instead, just as for the early design stages in the construction process, the material splits and quantities for each item will need to be assumed based on references and preliminary data. This information can then be used together with generic data of EFs to get a EC_{A1-A3}. The EC_{A4} and EC_{A5} can then be calculated according to sections 2.2.2 and 2.2.3.

2.5. Sensitivity Analysis

There are multiple uncertainties such as parameter uncertainties, methodology uncertainties and model uncertainties when performing an LCA. The parameter uncertainties are missing data, inaccurate data, and wrong inventory quantities, among others. The methodology uncertainties are, for instance, associated with system boundaries, while the model uncertainty refers to the simplifications entailed with conducting an LCA. Although being an uncertainty throughout the scope of a project, the parameters used in the early stages of the construction project are of extra uncertainty (Pomponi, De Wolf and Moncaster, 2018).

In the project's early stages, the material quantities are often estimated and far from finalised values. Simultaneously, the GWP data is probably generic and based on averages considering the exact material types are yet to be decided. Using the estimated quantities of material data together with the generic GWP data calls for a high level of uncertainty which pleads treatment to reduce the uncertainty.

One way of treating the uncertainty is through a statistical approach by producing an extensive range of results with varying input parameters. One way of doing this is through a Monte Carlo simulation.

2.5.1. Monte Carlo method

When calculating the upfront carbon, several variables must be considered. All quantities of materials, the GWP data associated with the respective material, the transport modes, transport distances and construction work activities must be considered at once. Using a Monte Carlo simulation, several variables can be varied simultaneously. Typically, several thousands of simulations are run where each variable is randomised between its minimum and maximum values determined by a probability distribution, resulting in a wide range of outcomes. The Monte Carlo simulations yields a range of results that can be assembled to illustrate the range and probability distribution of the results (Pomponi, De Wolf and Moncaster, 2018). The results from a Monte Carlo simulation can help understand the outcome of different scenarios and the likelihood of that outcome to occur. Furthermore, the Monte Carlo simulation can help identify the most significant variables impacting the final result.

2.6. Upfront carbon mitigation strategies

There are several ways to reduce the upfront carbon compared to the baseline scenario. For instance, mitigation of the upfront carbon can be accomplished by reducing the material usage, exchanging one material for a more climate improved one, using renewable energy and sourcing materials domestically. This section explains how one can reduce the upfront carbon in a building. After that, a more detailed section on alternative ways to produce the most common materials in a building, namely concrete and steel, is presented. Lastly, various concepts of how optimisation of a building can help reduce the carbon footprint are introduced.

Figure 2.6 shows nine different ways the upfront carbon can be reduced in a building. These are not all levers there are to mitigate the carbon footprint, but gives a range of measures in different categories.

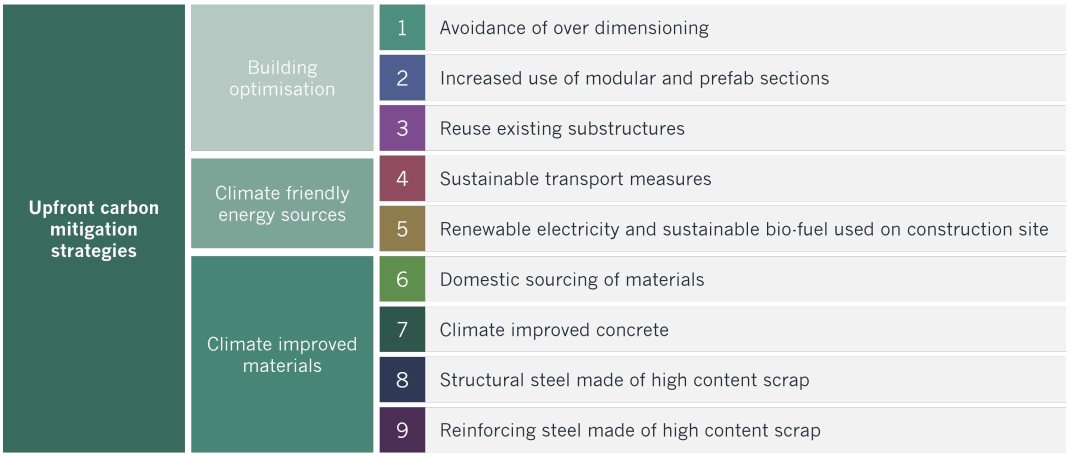


Figure 2.6.: Illustration of nine different mitigation strategies in three subcategories

Building optimisation

The building optimisation category includes strategies 1-3; avoidance of over-dimensioning, increased use of modular and prefabricated materials and reuse of existing substructures. This category refers to the measures where material use and waste generated can be decreased. The first strategy is explained in more detail under section 2.6.3. The second strategy is to use modular and prefabricated construction elements. While using these elements does not necessarily decrease the amount of material used in the construction, it can significantly impact the amount of waste generated. Waste generated in the construction industry is not only a source of GHGs but can also be a high cost in a project (Loizou et al., 2021). Exchanging on-site construction with prefabricated and modular elements can decrease the waste factor, which in turn reduces the construction installation process emissions, A5. The third measure, the reuse of existing substructures, is not applicable in all projects and is site-specific. However, the option of reusing existing building foundations should be explored. The building foundations represent a significant part of the carbon footprint and cost of a building. Reusing existing foundations may significantly change the scope of a project and introduce a more considerable risk. However, if the project succeeds, substantial savings of both GHGs and cost can be made (Henry Tayler, 2021). Reusing existing foundations will impact both the product and construction process stages (A1-A5) in the life cycle.

Climate friendly energy sources

This category of upfront carbon mitigation levers includes strategies 4-5, sustainable transport measures and the use of renewable electricity and sustainable bio-fuel on the construction site. In 2017 a third of the total GHG emissions, 17 $MtCO_2e$, in Sweden occurred due to domestic transport. Of the 17 $MtCO_2e$, heavy-duty and light-duty trucks accounted for 4.8 $MtCO_2e$. Much is being done within the sector to reduce the carbon footprint but what is available already today is various bio-fuels. The bio-fuels such as HVO and FAME can be used in some of the existing vehicle fleet. Comparing HVO100 with diesel purchased in Sweden regulated by the reduction obligation (2020), a reduction to the GHG emissions of approximately 74% can be achieved (Boverket, 2022a). Reducing the carbon footprint from the transport in a construction project would decrease the emissions of LCA module A4.

In the same way, the fuel used on site for the construction installation process could also be exchanged for bio-fuels which instead would decrease the emissions of LCA module A5. Moreover, in the construction installation process, the electrical supply could be contracted by a guarantee of origin, a document with the function of "providing evidence to a final customer that a given share or quantity of energy was produced from renewable sources (The European Parliament and the Council of the European Union, 2014)". Based on the guarantee of origin, the EF for the electricity used can be set to zero.

Climate improved materials

The last category is climate improved materials, including strategies 6-9; Domestic sourcing of materials, climate improved concrete, structural steel made of high content scrap, and reinforcing steel made of high content scrap. The three last strategies are explained in more detail in sections 2.6.1 and 2.6.2.

More than enabling local market involvement, domestic sourcing can also positively impact the carbon footprint. Sweden is a global leader in decarbonisation (IEA, n.d.) and has a relatively low emissions intensity (Statistics Sweden, 2022) meaning products produced within the country often has a low carbon footprint. Furthermore, domestic sourcing leads to shorter transport distances. Sourcing domestically means emissions from life cycle modules A1-A3 and A4 can be reduced.

2.6.1. Climate improved concrete

Globally, around 30 billion tonnes, or 72 000 billion cubic meters, of concrete is used yearly (Nature, 2021). To put the order of magnitude in perspective, the Baltic Sea has a volume of 21 billion cubic meters (Haapamäki, 2020). The relation means that the global concrete demand would be able to fill more than three Baltic Seas. Concrete has multiple areas of use, ranging from pilings and foundations to stairs and walls. After water, cement-based products are considered to be the most used material on Earth (Gagg, 2014). Cement is one of the most important constituents in concrete, and the production is both energy and emission-intensive. However, there are alternatives to cement that can be used in concrete to reduce the footprint of the concrete.

Green concrete is defined as either concrete that, to some level, substitutes the use of Portland cement with waste materials, is being produced in a process that mitigates the environmental impact or has high performance and life cycle sustainability (Suhendro, 2014). Since concrete is used to such a large extent, climate improved concrete has the potential to reduce the embodied carbon in the construction industry significantly.

The most common waste materials to use in concrete as a substitute to ordinary Portland cement are Ground Granulated Blast Furnace Slag (GGBS) and Fly Ash (FA) (Scrivener, John and Gartner, 2018). However, something that could be used more in the future is EAF reducing slags. Both waste materials are by-products of energy-intensive processes that impact the environment considerably. Utilising the by-products that otherwise would be wasted is energy and resource-efficient.

Ground Granulated Blast Furnace Slags

GGBS are by-products of the traditional production of pig iron. In concrete, the cement can be substituted with GGBS to achieve similar properties. GGBS can substitute cement up to high levels (Scrivener, John and Gartner, 2018). While substitution with GGBS is a good way of reducing the footprint of concrete, the availability is limited. Scrap-based steel-production has become more common, which halts the generation of GGBS. Also, the electrical route is becoming more popular, which also decreases the availability (Scrivener, John and Gartner, 2018).

Fly ash

FA is a by-product of electricity production in coal-fired power plants. While the availability of FA is higher than for GGBS, the quality is more variable. Approximately a third of the available FA has good enough quality to be used in concrete (Scrivener, John and Gartner, 2018). FA is not an as efficient substitute as GGBS, but fractions of 35% FA is common. Even though coal-fired power plants are being phased out for renewable substitutes, coal will continue to constitute a large fraction of the global energy mix. Thus, the availability of FA will continue to be high looking forward (Scrivener, John and Gartner, 2018).

Electrical Arc Furnace Reducing Slags

EAF reducing slags are by-products of the electrical route of steelmaking. While studies have shown that it is feasible to use EAF reducing slags to substitute the cement in concrete, there are no comprehensive sources of concrete being manufactured using the substitute (Li, Qiao and Ni, 2020).

Climate improved concrete - improved production process

Another route for reducing the climate footprint of concrete is by improving the production processes of the constituents. Cement is the main contributor to the overall footprint of concrete, and by improving the production process of cement, naturally, the footprint of concrete is reduced. One way to achieve this is by utilising Carbon Capture & Utilisation (CCU) as well as Carbon Capture & Storage (CCS). At this point, there are no extensive sources of cement produced with CCS and CCU, and the techniques are both expensive, entailing a significantly higher price for the concrete produced with this type of cement (Scrivener, John and Gartner, 2018).

2.6.2. Scrap based steel - Reinforcement and Structural

The primary function of structural steel is to build up the skeleton of the structure, and it is the element that connects everything and holds up the structure. The requirement for structural steel depends on the architecture of the building. A rebar is used to increase the tensile strength of concrete. It is common practice to use scrap in the reinforcement bars, but the amount of scrap in the rebar can vary.

Up until the mid-20th century, steel was mainly made using blast furnaces to produce pig iron together with open-hearth furnaces to drive off excess carbon. During this time, however, steelmaking underwent big technical advancements. The basic oxygen steelmaking process and the EAFs remapped the ways of making steel. The basic oxygen furnaces and EAFs enabled scrap to be reused in the process as input materials. Up to 25% of the input charge can be scrap steel in a basic oxygen furnace while up to 100% can be accomplished in an EAF (World Steel Association, 2022).

The scrap is considered waste, and using it to produce new steel is considered a way of cutting greenhouse gas emissions. However, the quality of steel produced from scrap may not be considered to be of the same level as steel made without scrap. The properties thus make scrap-based steel suitable for other applications, such as reinforcement bars (Ruth, 2004).

2.6.3. Over-dimensioning

Rather than only using more climate-friendly building materials, it might be possible to reduce the quantities too. The following section covers a few ways to improve building optimisation, enabling more efficient use of the materials in construction.

Minimising over-dimensioning and over-engineering

Structural designs can sometimes be over-dimensioned, and a focus on an optimised design can significantly reduce both cost and upfront carbon. (Pasanen et al., 2021). The case of over-engineering is especially true with steel (Material Economics, n.d.). As of today, the construction industry accounts for approximately half of the world's steel demand (World Steel Association, n.d.). According to Moynihan and Allwood (2014), who conducted a case study on 23 UK buildings, it is possible to use less material while still safely supporting the same loads in many cases. The 23 buildings were all steel-frame buildings, and the focus of the case studies was each beam's utilisation. The utilisation, in this case, is the ratio of the actual and maximum allowable performance values, or in simpler terms, an indication of excess materials. The results showed that the average utilisation rate for over 10 000 beams, when weighted by mass, was 54%. The results imply that almost half of the steel was redundant for the studied buildings.

Optimisation of reinforced concrete usage

Conventional concrete usually has a lower EF than regular steel, around 0.151 tCO_2e/t concrete produced (Boverket, 2022d) compared to 2.52 tCO_2e/t steel (Boverket, 2022c). However, as figure 2.2 illustrates, concrete still accounts for more than 40% of industrial building embodied carbon which is explained by the extensive amounts used. Therefore, optimising concrete usage in building design brings a high potential for reducing both cost and emissions.

From interviews with industry experts Alexander Landborn from ClimateWorks on the 17th of March (Interviewee: Landborn, 2022), as well as Henrik Nyberg from IN3PRENÖR AB and Louise Holmstedt from Bengt Dahlgren AB on the 28th of March (Interviewees: Nyberg and Holmstedt, 2022) it was understood that the concrete type usually is not varied across a building. The uniform use of concrete grades implies that high-strength concrete might be used even though certain areas only require low- to normal-strength concrete. The CO_2 footprint in relation to concrete strength class can be described according to equation 2.10, as well as table 2.3 (Fantilli, Mancinelli and Chiaia, 2019). The two relations are illustrated in figure 2.7 where the green line represents equation 2.10 and the red dots represents the relation from table 2.3

$$\text{kgCO}_2/\text{m}^3 \text{ of concrete} = \delta\sqrt{\text{Class of concrete}} \tag{2.10}$$

where $\delta = 46.5\text{kgCO}_2/\sqrt{\text{MPa}}$ (Fantilli, Mancinelli and Chiaia, 2019)

Table 2.3.: Environmental impact of concrete as function of concrete strength (Fantilli, Mancinelli and Chiaia, 2019)

Material	Concrete				Steel
	C25	C40	C60	C80	
CO2 Parametric Amount	[kg/m3]	[kg/m3]	[kg/m3]	[kg/m3]	[kg/kg]
	215	272	350	394	1.38

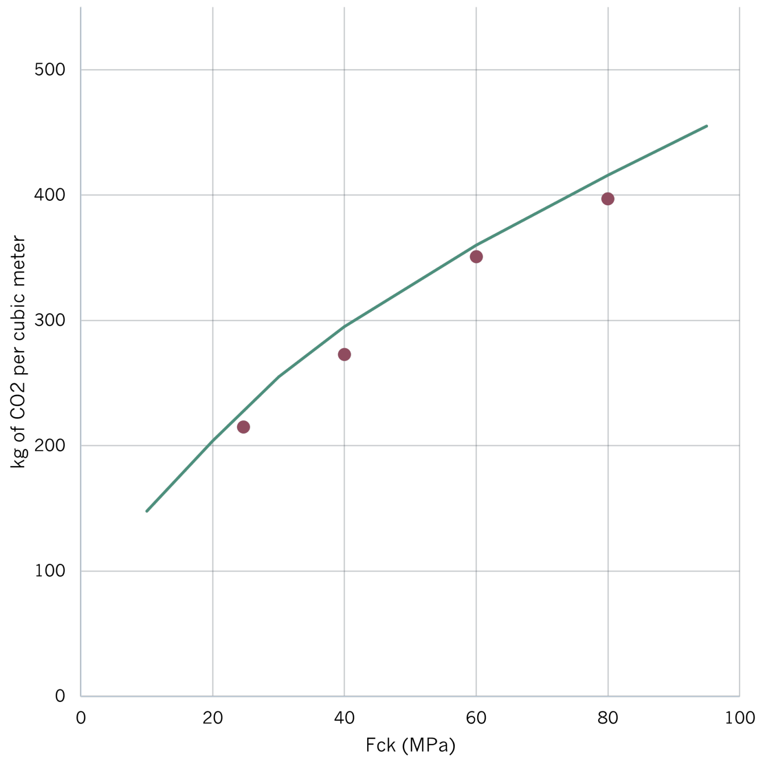


Figure 2.7.: Graph illustrating the relation between the CO_2 footprint and concrete strength, figure inspired by Fantilli, Mancinelli and Chiaia (2019)

Waste reduction

It is recognised that the construction industry generates much waste. According to the European Environment Agency (2020), EU-28 generated 374 million tonnes of construction & demolition waste in 2016, equal to more than 460 Golden Gate Bridges, which weigh around 800 000 tonnes (CNN Editorial Research, 2021). In 2000 it was reported by the World Resources Institute that in industrialised countries, one half to three-quarters of used materials were returned to the environment within one year (World Resources Institute, 2000). Furthermore, according to United Nations Environment

Programme (2020), approximately 25-30% of waste generated in the EU heirs from construction and demolition waste.

A first step in minimising construction waste can be to adopt the 3R-principles (Reduce, Reuse, Recycle). By striving to reduce, reuse and recycle as much as possible the construction materials on site, there is reason to hope that waste quantities, as well as associated emissions, will decrease. As described previously, one way to decrease waste is by using prefabricated and modular construction elements. However, there are other waste management strategies that can be adopted as well, such as engaging with contractors to reduce waste. This type of reduction could be realised through take-back clauses where contractors or subcontractors can guarantee that all materials delivered can be reused, recycled or at least redirected (LETI, 2020).

2.7. Supplier Selection

Although the procurement process will not be a central part of this thesis, it plays a role when suppliers are to be compared and evaluated from a sustainability perspective. Comparing and evaluating suppliers enable the possibility of putting theory into practice by setting requirements on suppliers to reduce their carbon footprint. Furthermore, the material choices and waste reduction can be addressed during this part of the construction process. As part of the procurement process, potential suppliers are selected and evaluated in a sequence according to

1. Identification of possible suppliers
2. Evaluation of suppliers
3. Selection of suppliers or further engagement (Weele, 2018)

In the identification step, a long list of potential suppliers and some critical data are identified and collected. In the following step, the evaluation of suppliers, a model is created to evaluate the suppliers, and initial information is collected through a Request for Information (RFI). In the last step, the selection of suppliers or further engagement, the selection of suppliers takes place based on the evaluation, sourcing strategy and available resources (Weele, 2018).

Usually, once the RFI has been answered, a Request for Proposal (RFP) is sent out to a selection of the repliers to the RFI. Among other things, the RFP has the purpose of creating a common basis for comparison, of getting detailed and comparable information about the suppliers and information about the products or services they provide. The RFP also acts as an assisting mechanism in processing a large amount of data efficiently (Weele, 2018).

A RFP contains multiple parts and can look differently from case to case. However, among many other things, the RFP includes supplier information as well as some kind of supplier survey where information can be gathered through a questionnaire (Weele, 2018). In this questionnaire and gathering of information, the sustainability perspective can be included to weigh suppliers according to their environmental impact in addition to quality and cost et cetera (Cherel-Bonnemaison et al., 2021).

Chapter 3.

Method

This chapter describes the method used to answer the five research questions. The method toward the final answer to each question will be described and motivated. Since several steps were conducted and iterated in parallel, the method does not follow a strict timeline. The sequence of sections follows the order of the research questions from one to five.

3.1. Defining the upfront carbon

The following section describes the method used to assess the upfront carbon from the H2GS Boden project. The calculations connected to the Boden project were central to answering all research questions. The outcome from the method used for assessing the upfront carbon laid the groundwork for the remainder of the thesis. Initially, a hypothesis was made to get an idea of the greater picture. After setting up a hypothesis, a detailed assessment was conducted together with a sensitivity analysis.

3.1.1. Data collection

Material Quantities

Considering the H2GS construction project to be in an early stage at the start of the calculations, the data on material quantities were mainly acquired from cost estimates. The material quantities were not flawless and had to be checked, evaluated, and supplemented prior to being used for the calculations. Where data was missing, it had to be collected with help from the person responsible for the respective business area. In some cases, the specified unit for the material quantity was unusable, e.g., specifying the amount of plumbing needed based on the area of each building. In these cases, reference projects were used, which then had to be rescaled to fit the needs of the H2GS construction project to estimate the amounts of material needed. In the few cases where there were no internal data on the material quantity splits nor any available reference projects, big suppliers of the respective components were contacted to get information on typical material and weight splits.

Emission factors

One Click LCA is a software that can be used to perform life cycle assessment calculations throughout the life cycle of a building. The software has an extensive, frequently maintained and updated database containing emissions data from multiple sources. The available emissions data are generic, manufacturer-specific or plant-specific, which can be used depending on the available data. There are clear indications whether a third party has confirmed the data, and all materials are ranked based on their environmental profile. The majority of data in the One Click LCA database contains background information, a brief description of the material, technical characteristics such as density and default values, the environmental profile containing the emissions carbon factor, and more. This database has served as the primary source of EFs together with a few supplements from other databases when the proper type of material has not been found in the One Click LCA database.

Transportation distances

Since the assessment took place during the early parts of the construction project, there was barely any data on exact travel distances, TD_{Mode}, needed to derive the EC_{A4} as described in 2.2.2. Instead, transportation distances, TD_{Mode}, were primarily based on modified standard lengths, while the emission factors were extracted directly from the Climate Database provided by the National Board of Housing, Building and Planning (road freight EF), as well as from Gibbons and Orr (2020) (sea freight EF). According to in-house logistics expert Nils Marnfeldt, there was substantial reason to assume that everything sourced outside Scandinavia is to be transported according to the steps presented below, but with unknown distances. The three modes of transportation were prepared for each material in the Excel model, with the assumed emission factors found in table 3.1 and distances for each transport leg illustrated in table 3.2.

1. Road transport from manufacturer to harbour A
2. Sea transport from harbour A to harbour B
3. Road transport from harbour B to construction site

As stated before, a vast majority of the materials were assumed to be transported according to table 3.2, thus implying that materials are assumed to be sourced somewhere within Europe but outside Scandinavia. In a few cases, other distances were assumed due to known manufacturer location, while some materials were assumed only to require one road transport.

Table 3.1.: Transport emission factors depending on transport mode

Mode	**Emission Factor (gCO2e/kg&km)**
Road transport emissions, fully laden	0.0757 (Boverket, 2022a)
Sea transport emissions	0.01614 (Gibbons and Orr, 2020)

Table 3.2.: Modified transport distances per transport leg used for the vast majority of materials and equipment

1st road transport	**Sea transport**	**2nd road transport**
200 km	2500 km	85 km

3.1.2. Implementation of calculations

A first hypothesis

As the project's first activity, a hypothesis was made as a starting point for further investigation. The hypothesis was made using a top-down approach, using basic materials data and comparing the H2GS construction project to case studies and benchmarking figures. The benchmarking figures were scaled to suit the size of the H2GS project. The idea was to quickly indicate what the final range could be and then compare that figure to the final results. The hypothesis was derived according to the following workflow:

1. Case studies on office buildings were read thoroughly. The case study results showed average distributions of the LCA modules A1-A5. Finding case studies on industrial buildings proved hard, so case studies on office buildings were used instead. The split between A1-A3, A4 and A5 was assumed to be equal to the one in industrial construction.

2. For modules A1-A3, typical material splits based on the carbon footprint were found for industrial buildings, where concrete and steel represent a vast majority

3. Based on material quantities for the H2GS construction project, the total footprint of concrete and steel could be calculated

4. The process equipment and all other items making up a functioning plant were modelled as 100% steel, and the weights were assumed to be the same as all steel going into the construction

5. The total footprint could then be reverse engineered based on the quantified footprint of concrete and steel together with the assumptions and findings in steps 1) through 3)

Detailed calculations

When the hypothesis was made, the approach was changed to a bottom-up one. The alternative approach meant quantifying the upfront carbon on a high level of detail for all the data available, avoiding as many assumptions as possible.

The calculations were performed in Microsoft Excel throughout the project. At an early stage of the project, alternative ways of calculating were explored. There are several life cycle assessment softwares available that can be used when calculating the carbon footprint of a building, e.g., SimaPro, openLCA and One Click LCA. Everyone interviewed with experience in life cycle calculations of constructions recommended One Click LCA, which is why a license was acquired.

While One Click LCA is a great software that has served as the primary source of emissions data, it is designed to calculate the footprint of conventional buildings. Since this project's scope includes the process equipment, on-site infrastructure, and utilities apart from the buildings themselves, the software could not be used for all parts, so Excel has been used in parallel. One Click LCA has also been beneficial in confirming the calculations in Excel by comparing several parts in the software.

In Excel, the calculations were performed based on cost estimates already in place. The cost estimate containing information on material quantities was used as the primary source of truth throughout the project. The calculations were made with a high level of granularity to categorise the carbon footprint in any way wanted for the later stages of the project. All data on estimated material quantities were assigned to a specific area in accordance with the actual H2GS site layout, which meant a high level of detail could be achieved. To illustrate an example, this meant that the footprint of rebar used in the foundations could be found for one specific building or function. One crucial aspect that was kept in mind throughout the calculations was to have a high level of traceability, with transparent sources for each assumption made.

Calculating the A1-A3 upfront carbon

The theory introduced in 2.2.1 was used to calculate the contribution of modules A1-A3 to the total carbon footprint. Considering the H2GS construction project to be in the early stages where construction is yet to commence, assumptions had to be made regularly. Those assumptions were primarily estimations of material quantities, compositions, weights, and other necessary variables. The assumptions were based on reference data or discussions and conclusions with internal or external expertise. The specified material quantities in the cost estimations were stated in several units. In cases such as for concrete, where amounts needed were assumed based on the volume needed, equation 2.2 could be used straight away. For other cost items measured in units such as pieces, similar equipment or materials had to be identified and used to assume the weights or volumes. To exemplify such an item, a particular water tank could be stated as one piece together with dimensions and a description of the application. This data was then used to search for a reference with more detailed information on weights and material compositions. The detailed data on weights and material splits could then be used as estimates for equation 2.2. These two types of methods used to derive the total EC_{A1-A3} are illustrated in figure 3.1.

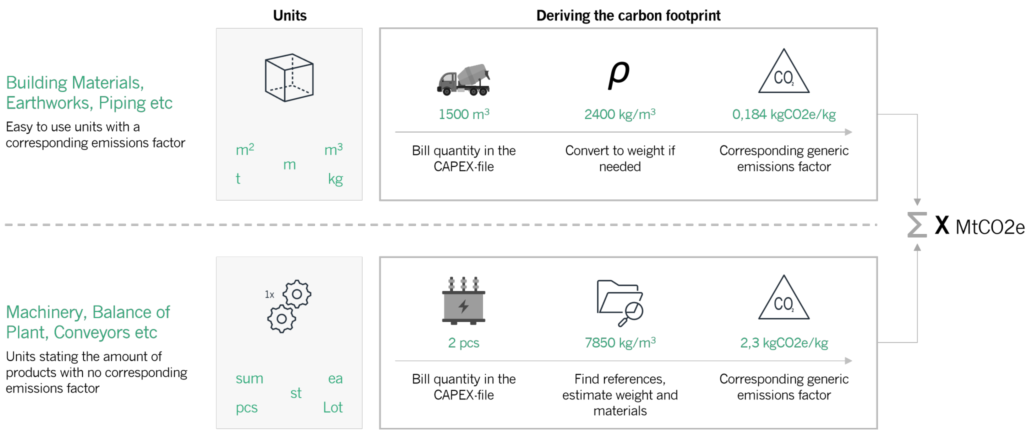


Figure 3.1.: Illustration of how A1-A3 emissions were derived with example figures

Calculating the A4 upfront carbon

To calculate the contribution of module A4 to the total carbon footprint, the theory presented in section 2.2.2 was used. In the cases where exact travelling distances were known, those were used instead of the values presented in 3.2. The different TEF_{Mode} in table 3.1 depend on the transported weight. The data on weight for each material was reused from calculating EC_{A1-A3}. Transport modes for each material were assumed according to the presumed country of origin, e.g., a material assumed to be produced in Germany entailed three shipping legs as described above. Furthermore, all return trips for each mode of transport were assumed to serve a purpose and have consequently been excluded from the calculations of $EC_{A4,i}$.

Calculating the A5 upfront carbon

The contribution of module A5 was calculated according to section 2.2.3. The material quantities used were neat, meaning no excess material had been accounted for. Therefore, it was assumed that an extra percentage of each material was to be delivered for contingency. This extra percentage is assumed to be wasted and thus yields an A5 emission. Waste factors were extracted from the Climate Database provided by the National Board of Housing, Building and Planning and applied to the corresponding construction material or equipment to the best extent possible. The used waste factors are listed below. The EC_{A5w} was then calculated according to equations 2.7 - 2.8 provided in theory section 2.2.3.

Table 3.3.: Used waste factors and materials they are attributed to

Waste (% of total weight)	Material(s) attributed to
3	Foundational concrete and concrete walls
5	Concrete blocks and brick walls
9	Reinforcement steel (rebar)
5	Structural steel
0	Prefabricated concrete elements
For all materials and equipment without a waste factor listed in the Climate Database, assumptions ranging from 0% - 5% waste were made depending on degree of prefabrication and assumed material compositions.	

The two scenarios provided by One Click LCA on electricity use and fuel use were used to estimate the energy use on site. Equation 2.9, together with the emission factors in table 3.4 below, were then used to derive the site activity emissions entailing fuel and electricity use. The emissions factors used were sourced from the climate database provided by the National Board of Housing, Building and Planning. The electricity EF is based on the Swedish average between the years 2015 and 2017. The Diesel EF is based on the reduction obligation from 2020, where the amount of bio-diesel is set to 21%.

Table 3.4.: Electricity and fuel (diesel) emission factors (Boverket, 2022a)

Electricity EF (kgCO_2e/kWh)	Diesel EF (kgCO_2e/l)
0.037	2.67

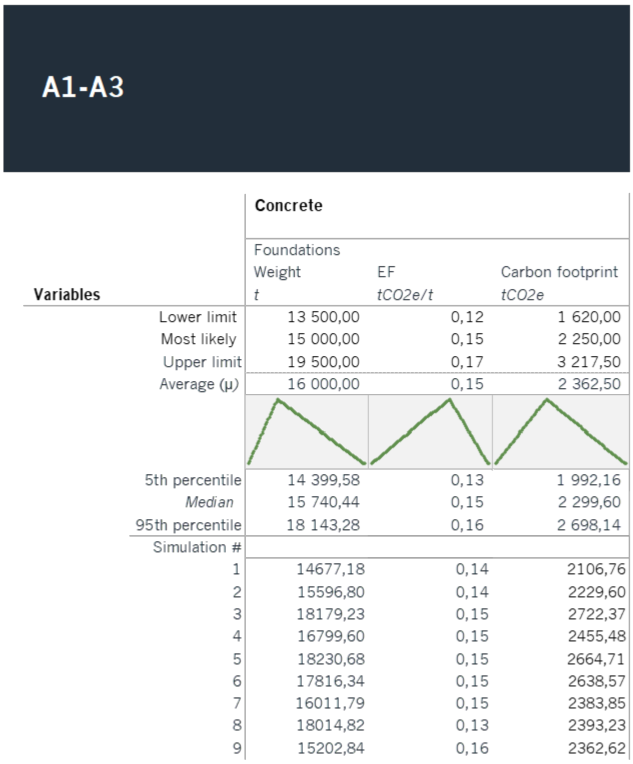
Summarising the total upfront carbon

Finally, EC_{A1-A3}, EC_{A4} and EC_{A5} were summarised in two different sets. One set according to the whole scope with buildings, on-site infrastructure and process equipment and another set according to the scope of a climate declaration. The footprint for both those cases was split in three ways; one based on the LCA stages A1-A3, A4 and A5, one based on the materials and one based on the layout of the production site.

3.1.3. Sensitivity analysis

When the detailed calculations of the total carbon footprint for the H2GS construction project had been made, a sensitivity analysis of the results was conducted. A Monte Carlo simulation was created from scratch in Excel, where all variables could be varied simultaneously. The variables varied were emissions factors, weights, volumes, transport distances, and waste factors, among others. Every variable was assigned a lower limit, a most likely value and an upper limit forming a triangular distribution. The sum of the calculations for the most likely values was identical to the results from the detailed calculations of the total carbon footprint. All the lower and upper limit values were chosen based on different scenarios. The emissions factors can vary depending on where the materials are sourced from, if the materials are climate improved, and how they are manufactured. The material quantities are estimates, meaning they can be higher and lower in practice, so all material quantities were varied between an upper and lower limit. The Monte Carlo model used 8000 simulations where every variable was randomised within the triangular distribution. For each simulation, the contributions to the total upfront carbon were summarised and then presented in a histogram and a scatter plot. A tornado chart illustrating the variables with the biggest impact on the overall footprint was also made. The tornado chart illustrates the contribution uncertainty of each variable. A cut-out of the complete Monte Carlo simulation model can be seen in figure 3.2.

Each variable influencing the upfront carbon is assigned a lower and upper limit and a most likely value. The triangular distribution is illustrated for each column. For the majority of variables, the distribution was not uniform. It was assumed that each variable was more inclined to increase rather than decrease for contingency. Thus, the difference between the upper limit and most likely value was more significant than between the lower limit and most likely value. The cut-out shows example numbers for the first nine simulations of the A1-A3 concrete foundation's contribution to the total upfront carbon. The results from the Monte Carlo simulations were then analysed and reflected on.



A1-A3

Variables	Concrete Foundations Weight *t*	 EF *tCO2e/t*	 Carbon footprint *tCO2e*
Lower limit	13 500,00	0,12	1 620,00
Most likely	15 000,00	0,15	2 250,00
Upper limit	19 500,00	0,17	3 217,50
Average (μ)	16 000,00	0,15	2 362,50
5th percentile	14 399,58	0,13	1 992,16
Median	15 740,44	0,15	2 299,60
95th percentile	18 143,28	0,16	2 698,14
Simulation #			
1	14677,18	0,14	2106,76
2	15596,80	0,14	2229,60
3	18179,23	0,15	2722,37
4	16799,60	0,15	2455,48
5	18230,68	0,15	2664,71
6	17816,34	0,15	2638,57
7	16011,79	0,15	2383,85
8	18014,82	0,13	2393,23
9	15202,84	0,16	2362,62

Figure 3.2.: A cut-out of the Monte Carlo simulation model in Excel with example figures

3.2. Plug- & Play model

The plug- & play model was at first supposed to be a fully scalable tool to calculate the upfront carbon of a future steel mill plant. The tool was meant to estimate the upfront carbon for a hydrogen plant, direct reduction plant, and steel plant. In other words, a tool able to rescale and calculate the emissions of everything included in the Boden project. Throughout the thesis, it became more obvious that there was neither enough data nor time to be able to create such a scalable tool. After some time, the plug- & play tool was limited to being able to rescale only the upfront carbon of a hydrogen production plant. Furthermore, discussions on when and how the scalable tool was supposed to be used took place. The discussions led to the conclusion that it should be used in pre-feasibility and feasibility studies to identify hotspots of CO_2e and to help allocate where the focus should be put to reduce the upfront carbon. With the results from the discussions and limitations, it was decided to incorporate the thesis work of upfront carbon into an already existing tool rescaling a different physical quantity. Therefore, work began on finding the best strategy to incorporate upfront carbon calculations into the existing tool.

The already existing tool had been created in an Excel file, which is where the carbon calculations were to be added. In a database, all materials and equipment constituting the Boden hydrogen plant had been extracted. The database sourced and summed each material and equipment from the same cost estimate that had been used as the source of truth for the upfront carbon calculations of the Boden project. Since the thesis involved some restructuring of the original file, where upfront carbon had been added to each cost item, it was easy to add that to the plug- & play model. The database where the summing of the Boden hydrogen plant equipment and materials took place did, however, contain more materials and equipment than that used in Boden. In order to accommodate other choices of equipment than that used in the base case, this was important. Therefore, new calculations for certain equipment such as storage tanks, compressors, and technologies had to be conducted. The calculations were performed in the same manner as described in sections 2.2.1 through 2.2.3, e.g., by estimating weights and materials and choosing the appropriate emission factors.

Regarding the scalability of the tool, there was already such a function installed in the tool. This, however, had to be reevaluated to see whether the scaling factors were appropriate for upfront carbon as well. This was done manually by a row-by-row analysis of each material and equipment that were to be rescaled. The actual scaling was made possible by relating the desired input, meaning scaling factors, with the references from Boden.

Furthermore, it is important to remember that the scalable plug- & play model was constructed to be used before commencing construction. Therefore, much standardising was required. The rescaled emissions for each piece of equipment were presented in an output sheet, allowing for easy analysis of hotspots. Again, it is important to stress that the idea of the model is to calculate the emissions to be able to manage and mitigate them long before the first sod.

3.3. Carbon mitigation strategies

In parallel with calculating the upfront carbon according to section 3.1, general ways of reducing the carbon footprint were identified. Defining the upfront carbon and creating the plug- & play model serves to define and calculate the hypothetical carbon footprint for the as-built construction that eventually will be built. This part of the project, however, is used to find ways of reducing that hypothetical carbon footprint by discovering and implementing different upfront carbon mitigation strategies as explained in section 2.6.

The first step in this part of the thesis was to perform a literature study, exploring different ways of reducing the upfront carbon in a construction. The idea was to find several different ways to reduce the calculated upfront carbon in buildings and then evaluate each mitigation strategy.

Initially, several sources were read to identify the most common ways of reducing the upfront carbon to get an overview. All identified mitigation strategies were listed in a document. In the cases where two or more strategies were similar or identical, they were combined into one common mitigation strategy. An in-depth examination into every strategy was conducted when a sufficient number of strategies had been found. In the in-depth examination, the technical basis for each strategy was discovered to get a theoretical background to each of the potential upfront carbon reduction strategies. The three strategies with the largest carbon footprint reduction potential were then researched more thoroughly, which lays the basis for sections 2.6.1, 2.6.2 and 2.6.3.

When the ways of reducing the upfront carbon were evaluated, an expert interview was arranged with Alexander Landborn to discuss the identified mitigation strategies (Interviewee: Landborn, 2022). Landborn gave his view on what he found to be the most common methods of reducing the carbon footprint and the most effective ones. Landborn also explained how a few strategies could be combined into suitable categories and where the focus should be put when depending on the construction timeline. Following the interview with Alexander Landborn, the mitigation strategies were further refined. In total, nine mitigation strategies were identified within three main categories. The focus was not solely on finding mitigation strategies for the H2GS Boden project but rather on finding general strategies that could be implemented if deemed applicable. The most realistic upfront carbon mitigation measures at the point of the analysis were put in relation to the base case by altering the input parameters one by one. These were using structural steel with a high content scrap, climate improved concrete, sustainable transport measures and use of renewable electricity and sustainable bio-fuel on the construction site.

Structural steel with a high content scrap

To this mitigation strategy, the EF of all structural steel was reduced by 64% by exchanging the baseline type of primary material structural steel with scrap-based structural steel according to the Climate Database provided by the National Board of Housing, Building and Planning (Boverket, 2022a).

Climate improved concrete

In this case, the EF of all ready-mix made concrete (i.e., concrete that is delivered by truck and poured at the site) was reduced. By exchanging the baseline type of concrete, where cement is the binder, with a concrete type where a portion of that cement has been replaced with alternative binders according to the Climate Database provided by the National Board of Housing, Building and Planning, the footprint was reduced by 25% (Boverket, 2022a).

Sustainable transport measures

To this reduction lever, the TEF_{Mode} for road transport was changed from being based on diesel according to the reduction obligation of 2020 to HVO100 according to the Climate Database provided by the National Board of Housing, Building and Planning. The change from diesel to HVO100 enables a reduction to the TEF by 73% assuming the energy use in MJ/tonnekm of a truck remains unchanged when changing the fuel type (Boverket, 2022a).

Renewable electricity and sustainable bio-fuel on the construction site

To this mitigation strategy, the EF_{Diesel} was exchanged for EF_{HVO100} according to the Climate Database provided by the National Board of Housing, Building and Planning. The $\text{EF}_{Electricity}$ was set to zero based on the potential of having a guarantee of origin in place. The change from diesel to HVO100 enables a reduction in emissions factor by 74% (Boverket, 2022a).

3.4. Supplier comparison and evaluation

Many of the mitigation strategies can be implemented into actual use during the procurement process. With knowledge acquired on reducing the carbon footprint, the next step was to set up a method on how the suppliers can be compared and evaluated. The first part of the supplier comparison and evaluation meant finding a way to gather data systematically. With little previous knowledge in supply chain management, this meant asking fellow students specialising in supply chain management how this is done in real-life practice — this way, a bunch of material was acquired, including material from guest lectures on this specific subject.

With the material from the guest lectures received, several keywords were found that thereupon could be further investigated. Eventually, it was found that the most suitable way to gather data is through the procurement process and, in particular, the RFP.

The second part of the supplier comparison and evaluation meant coming up with a standardised questionnaire where all suppliers could be evaluated on common terms. This part was iterated many times in two general versions. One focused on comparing the suppliers through a set of questions, and in the other, the suppliers were asked to calculate their contribution to the upfront carbon. The requirements from this piece of work were that the received data should be easy to compare and come to actual use. Furthermore, the questionnaire should be possible to fill in without any prior knowledge in the area. The version with questions focused on getting information on the supplier's emission reduction targets.

Eventually, the supplier comparison and evaluation were decided to be based on the supplier's estimated contribution to the overall upfront carbon. This way of comparing enables the possibility to compare the supplier's estimates to the calculations made during this master's thesis project. Moreover, this way of comparing also meant that the detailed calculations made in this project could be updated continuously.

The document was prepared with the requirement of being simple to use as the main design parameter. The design criteria meant much effort was put into making clear and easy to read instructions which were tried out on colleagues with limited experience on the subject. The suppliers were asked to estimate their A1-A3, A4 and A5 emissions, preferably through EPDs of the supplied products. In the cases where the suppliers had no available EPDs, they were encouraged to create one and meanwhile, they were allowed to estimate the impact through the attached instructions. Finally, the outcome was discussed and presented to the person responsible for the RFP where this piece of work will be included.

3.5. Downstream value of upfront carbon assessments

To answer what downstream value embodied and upfront carbon calculations and reporting might generate, interviews with stakeholders were planned to be held. Questionnaires were sent out via email for potential interviewees who could not participate live. All interviews were held in Swedish; hence, the questions have been translated into English for the report. The focus of each interview was to see what the respective stakeholder's view was on the topic of the thesis work, what perceived value it brings and whether they find it important. The stakeholders interviewed were:

1. A potential customer
2. The Swedish Environmental Protection Agency (Sv. Naturvårdsverket)
3. The Swedish National Board of Housing, Building and Planning

Out of these, only the potential customer could attend a formal interview, whereas the other three answered via email.

The questions that were asked to the respective stakeholder is attached in Appendix A. Aside from the presented questions, further follow-up questions were asked if deemed necessary.

Chapter 4.

Results

This chapter presents the results from the implementation of calculations and sensitivity analysis. Furthermore, the results of the plug- & play model are presented. After that, the results from the carbon mitigation strategies and the document for the supplier comparison and evaluation are presented. Finally, the results from the interviews regarding downstream value are presented. The results are presented in the same sequence as in chapter 3. Numbers not presented as a percentage have been normalised to a factor of 1, and are therefore dimensionless. The corresponding shares are however still correct, even though no actual quantities are shown.

4.1. Defining the upfront carbon

4.1.1. Top-down approach

The hypothesis made during the first weeks through a top-down analysis is presented in the following section. The results from the top-down approach are normalised to 1 for comparison. The results were derived according to the steps from the method explained in section 3.1.2 and further detailed in figure 4.1. The figure shows how the estimated data for $EC_{A1-A3,concrete}$, $EC_{A1-A3,rebar}$, $EC_{A1-A3,structuralsteel}$ were used to derive a hypothesis for the total upfront carbon in the top.

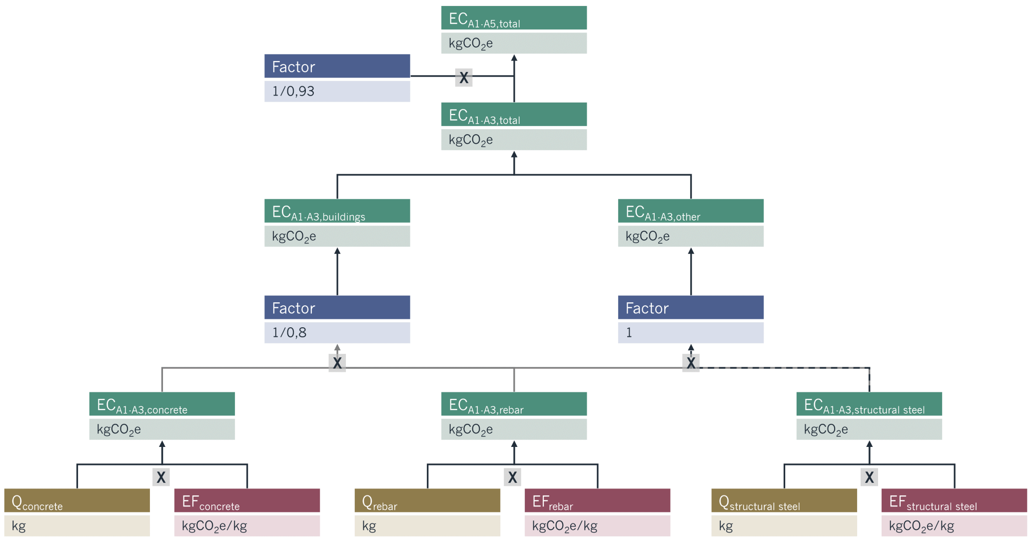


Figure 4.1.: Driver tree showing the calculation steps to derive the hypothesis

According to the first step, splits between A1-A3, A4 and A5 were gathered from a case study made by Joint Research Centre (JRC) which are presented in figure 4.2. For the analysis, the average of the two case studies was chosen according to table 4.1. According to the second step, typical splits on A1-A3 per building element were also found in the same case study made by JRC. The contribution from the substructure and superstructure based on the GWP was 80% for the building with a concrete frame which was used as an estimate (European Commission and Joint Research Centre, Gervasio and Dimova, 2018). In the third step, the estimated carbon footprint of the superstructure and substructure were calculated based on the material quantities in the cost estimate. The substructure was assumed to be dominated by the concrete and rebar. The superstructure was assumed to be dominated by structural steel. The fourth step was to make a modelling estimation that all items making up the functional plant, apart from the buildings themselves, was made of 100% steel and that the amount of steel was equal to the amount of structural steel going into the construction. In the last steps, all gathered data and estimates from the previous steps were combined to develop the final hypothesis.

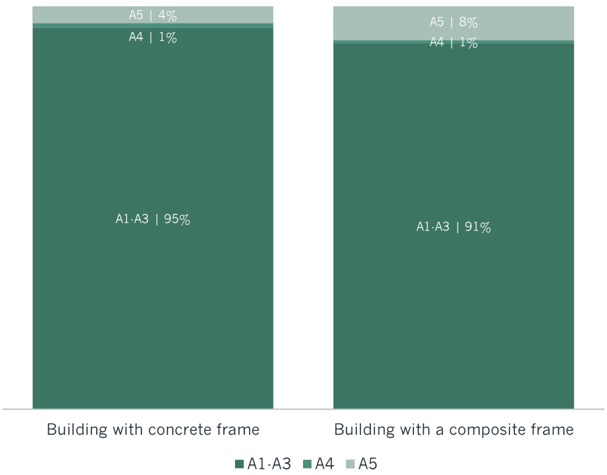


Figure 4.2.: Results from the case studies made by JRC of two different buildings, figure inspired by European Commission and Joint Research Centre, Gervasio and Dimova (2018)

Table 4.1.: Average splits on A1-A5 used for the analysis

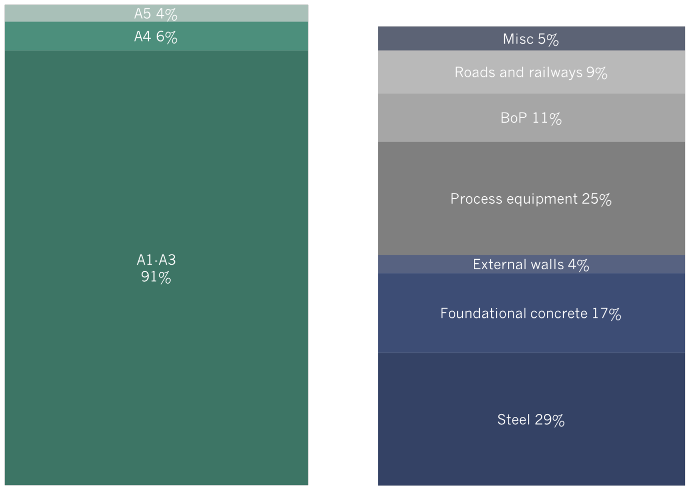
	A1-A3	A4	A5
Average	93%	1%	6%

4.1.2. Bottom-up approach

The results from the detailed bottom-up calculations are presented in the following section. As mentioned in the method, section 3.1.2, the results are presented for two different scopes together with three different splits.

Whole project scope

All items going into the site are considered in the whole project scope, which means that these results are not comparable to regular assessments of buildings. Compared to the top-down approach, the bottom-up approach for the whole project scope was approximately 1.4, meaning 40% higher than the value derived from the first hypothesis.



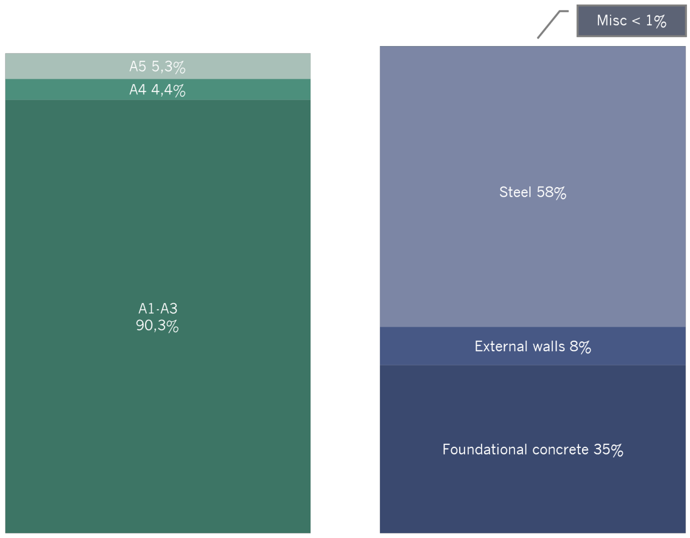
(a) Split on LCA modules **(b)** Split on materials

Figure 4.3.: Illustrations of upfront carbon splits for the whole project scope

Figure 4.3a shows the split of upfront carbon on the modules A1-A3, A4 and A5, while figure 4.3b shows the split of the total upfront carbon (A1-A5) of the different construction materials and equipment. The blue area represents the total upfront carbon from actual construction materials, while the grey area includes materials and equipment for different on-site functions. Balance of Plant (BoP) includes auxiliary equipment such as electrical equipment, piping, plumbing, water systems, et cetera. Miscellaneous items belonging to both the blue and grey areas are summarised in “Misc”, including fire protection equipment, storage containers, vehicles, heating, ventilation, and air cooling (HVAC), and lighting, among other things.

Climate declaration scope

In this scope, the elements included in a climate declaration are considered. Note that there is no obligation to conduct climate declarations for industrial buildings. In most cases, references and benchmarks are based on residential buildings, offices, or school buildings. Furthermore, climate declarations should be made as close to the completion of the building as possible. The resulting figure from this scope was 54% smaller than that from the whole project scope.



(a) Split on LCA modules **(b)** Split on materials

Figure 4.4.: Illustrations of upfront carbon splits for the climate declaration scope

Figure 4.4a shows the split of upfront carbon on the modules A1-A3, A4 and A5, while figure 4.4b shows the split of the upfront carbon on the different materials. In the climate declaration scope, the miscellaneous items account for less than 1%. The split of materials is based on modules A1-A5.

4.1.3. Sensitivity analysis

The results from the Monte Carlo model can be seen in figures 4.6, 4.5 and 4.7. Note that the Monte Carlo model only was used for the whole project scope and not the climate declaration scope. In the graphs, 1 on the x-axis is the baseline value for the whole project scope, and the decimals represent the fractional variation to the baseline.

Figure 4.5 shows the cumulative distribution from the Monte Carlo simulations. Figure 4.6 shows the results from the Monte Carlo simulations in a histogram. The height of each bin represents the occurrences from the simulations within the range, and the horizontal axis shows the upper limit of the corresponding bin. The 5th and 95th percentile have also been marked out in the histogram. The mean, 5th and 95th percentiles, min and max values are presented in table 4.2.

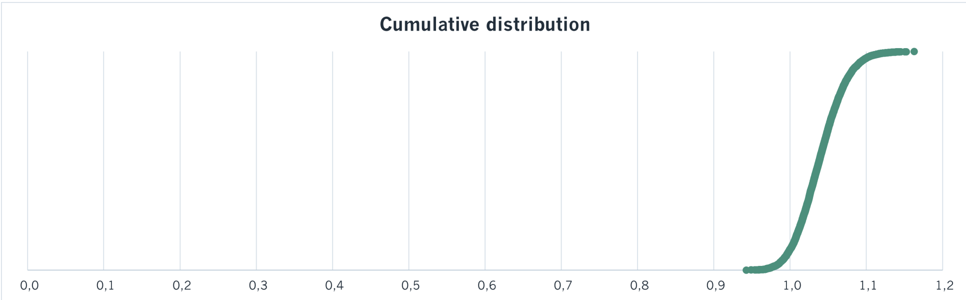


Figure 4.5.: The cumulative distribution of the Monte Carlo simulations

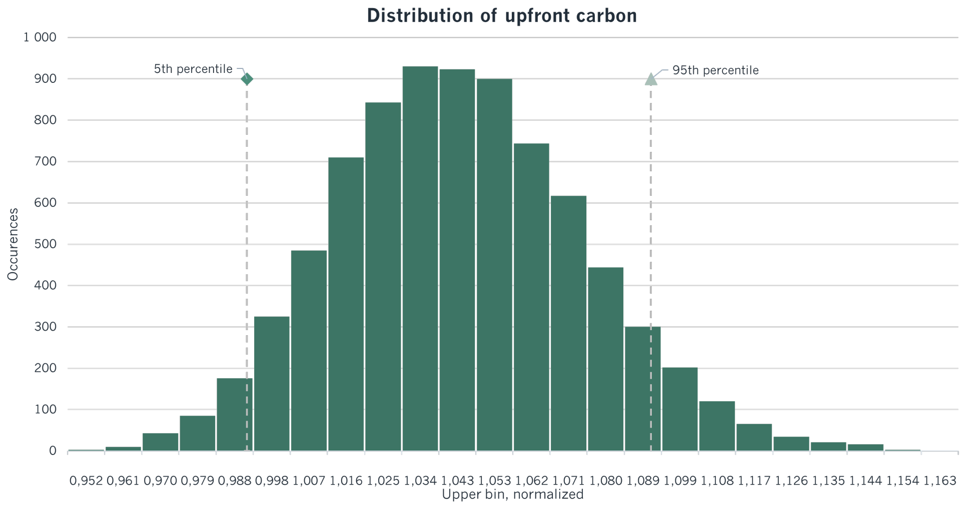


Figure 4.6.: Results of the Monte Carlo simulations in a histogram

Table 4.2.: Summary data from the Monte Carlo simulations

Mean	5th percentile	95th percentile	Min	Max
1.039	0.991	1.091	0.943	1.163

Figure 4.7 shows the relative contribution to the total footprint at P5 and P95 for the ten variables with the highest relative contribution. To exemplify, at P95, the contribution from heavy structural steel in LCA modules A1-A3 accounts for 28% of the total upfront carbon, while the corresponding figure is 20% at P5.

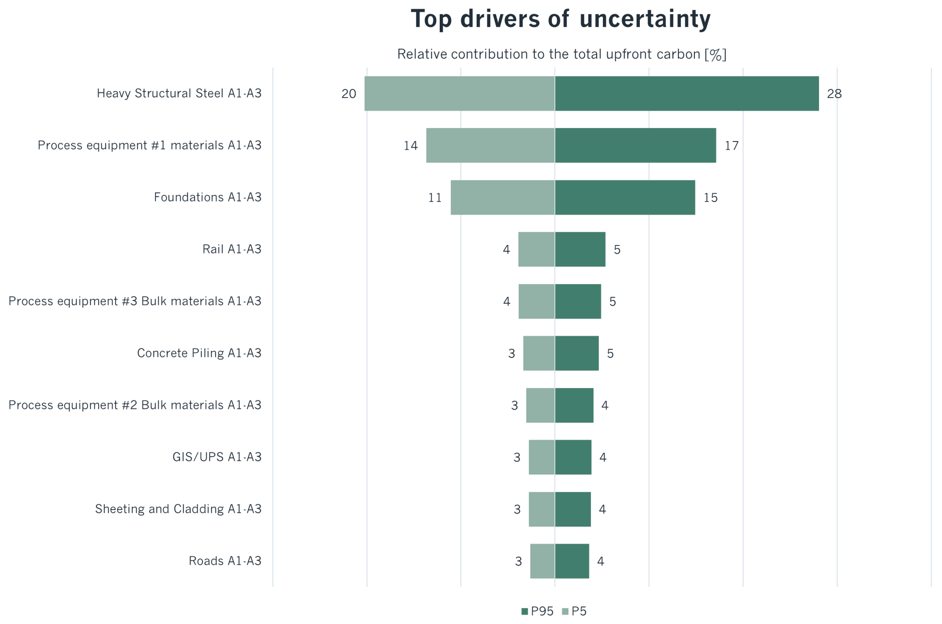


Figure 4.7.: Results of the Monte Carlo simulations in a tornado-chart

4.2. Plug- & Play model

As previously mentioned, the aim of the plug- & play model was to create a tool able to rescale the upfront carbon of the hydrogen plant in Boden to a new production plant. Therefore, probable areas of use include tendering processes and identification of CO_2e hotspots. After the reevaluation of the tool, described in section 3.2, the resulting tool became an expanded version of an already existing scaling tool. After incorporating upfront carbon, this resulted in a functional tool enabling the possibility to estimate the upfront carbon of a planned hydrogen production plant long before commencing construction. Thus, the primary goal of CO_2e hotspot identification was achieved.

The plug- & play model results shown in the Excel model are presented similar to those of the Boden calculations, meaning that the A1-A5 emissions are displayed in buckets of A1-A3, A4, and A5 emissions, respectively. The results are presented in different construction site elements, such as:

- **Mechanical** – meaning actual equipment such as electrolyser, storage tanks and compressors
- **Buildings and foundations** – including all necessary buildings, i.e., offices and administration buildings
- **Earthworks** – such as emissions from earthmoving machinery

- **Electrical** – in example cabling, transformers and similar

The resulting splits on the LCA modules of the rescaled hydrogen production sites were similar to other benchmarking, such as the total Boden calculations, pointing to an accurate model. Furthermore, when testing the model with the exact same criteria as required in Boden, the resulting total footprint was within 4% of that of the Boden hydrogen facility.

4.3. Carbon mitigation strategies

In figure 4.8 the potential reduction of the total upfront carbon based on four mitigation strategies is presented. The width of each rectangle represents the addressable emissions (e.g., the contribution of upfront carbon to the baseline scenario for the whole project scope). The height shows the relative reduction to the overall upfront carbon for the specific mitigation strategy. The area of each rectangle thus shows the product of the addressable emissions and the potential reduction leading to the actual reduction in the total upfront carbon compared to the baseline case.

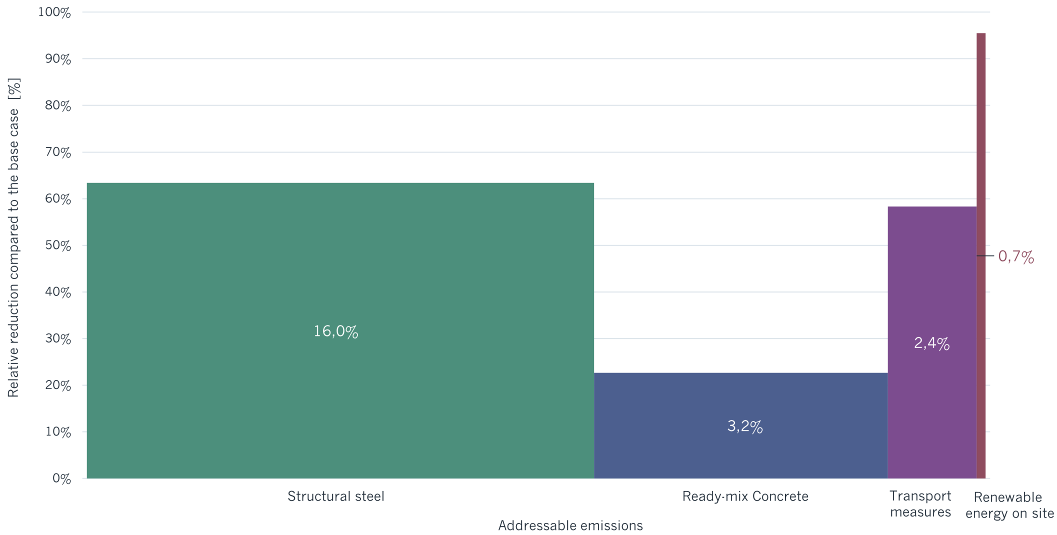


Figure 4.8.: A variable width column chart showing the potential reduction to the total upfront carbon for four mitigation strategies

4.4. Supplier comparison and evaluation

The final document made for the RFP was titled "Sustainable supplier information form", and an excerpt can be found in Appendix B. The document contains a short introduction and a section explaining what emissions are being asked for. This introductory page is followed by a few pages where the process of calculating the A1-A5 emissions is introduced, exemplified, and illustrated to make it possible to calculate the emissions with no previous experience. The results from the example calculations of A1-A5 are then presented to give the reader an idea of a typical split between the different LCA modules. Supplementary material in the form of typical EFs and links to relevant websites and databases are attached in the Appendix of the information form. To be noted is that the form found in Appendix B is an example of how this could be done, and not a guideline for how it is being or should be done.

4.5. Downstream value of upfront carbon assessments

Upon conducting the interviews described in section 3.5 and Appendix A, the answers indicate that there is a value in calculating and communicating the upfront and embodied carbon of a large-scale industrial facility. Calculations of this kind will probably become more frequent and essential, and they may even be required in the future, according to the National Board of Housing, Building and Planning. However, developing and executing strategies to mitigate emissions resulting from new construction is critical for the calculations to bring value. The following paragraphs contain the key takeaways from the respective stakeholder interview.

Potential customer From the customer perspective, there could be a particular interest in this kind of engagement in the early stages of the project since production is yet to begin. As of right now, and in the coming years, construction related emissions are the primary source of emissions related to H2GS. According to the potential customer, it is thus valuable to see an engagement in reducing the upfront carbon. In the potential customer's evaluation of their suppliers, it is usual for suppliers to provide information on any initiatives to reduce emissions in free text. This part of the evaluation could be interesting to H2GS and could be a place worth delving deeper into. Furthermore, reports and articles on topics such as reducing construction-related emissions, e.g., embodied and upfront carbon, are regularly occurring on social media such as LinkedIn, meaning there is a growing knowledge of the problem. Therefore, potential growth in demand for reporting and calculating embodied and upfront carbon is a possibility (Interviewee: Customer, 2022).

The Swedish Environmental Protection Agency According to Katarina Warmark, Climate Analyst at the Swedish Environmental Protection Agency (Sv. Naturvårdsverket), the possibility of growing demand for embodied and upfront carbon calculations and mitigation strategies is not entirely off. When asking Warmark about the exemption of industrial facilities in the requirements of Climate Declarations, she answered that, according to the National Board of Housing, Building and Planning, the requirements might expand in the future. Furthermore, Warmark assumes that similar calculations will become more common in the future. Increased knowledge, easy-to-use software, and a growing interest in contributing to climate impact mitigation strategies are probable to increase the frequency of similar work. Regarding the downstream value, Warmark's perception was that it is dependent on what phase the project is in. In the case of new construction, introducing mitigation strategies can be of great value (Interviewee: Warmark, 2022).

The National Board of Housing, Building and Planning The perception from the National Board of Housing, Building and Planning was that organisations in general rarely calculate the embodied or upfront carbon of new construction, which is why requirements of climate declarations were first established. The reason is to reduce the climate impact of construction and increase the knowledge and understanding of the emissions associated with buildings. To answer why industrial buildings are exempt from climate declarations, the National Board of Housing, Building and Planning referred to their website. The website states that due to specific structural demands, the construction materials used will vary greatly. The National Board of Housing, Building and Planning argues that these variations complicate the comparability of a climate declaration (Boverket, 2021b). When asking the National Board of Housing, Building and Planning if they anticipate an increased frequency and importance of calculating and developing mitigation strategies for embodied and upfront carbon, their answer was "yes". On the topic of incentives and increased requirements for reducing construction emissions, the National Board of Housing, Building and Planning referred to a new proposal from the Swedish government concerning setting up limit values for climate impact from buildings. The new proposal aims to, amongst other things, investigate and provide recommendations on how limit values for new construction could be introduced before 2027, which is when climate declarations were first proposed to be expanded. To support the new proposal, a review of reference values of the climate impact of varying buildings made by the Royal Institute of Technology will be used (Boverket, 2022e). Regarding the National Board of Housing, Building and Planning's stand on industrial companies voluntarily conducting calculations similar to climate declarations, such as the thesis work, they state that all actions to mitigate the climate impact from construction are positive and will be needed in the future (Interviewee: Boverket, 2022).

Chapter 5.

Discussion

5.1. Defining the upfront carbon

The following sections discuss the methodology used to calculate the upfront carbon, such as what sources of error might create uncertainty in the results. Furthermore, the discrepancies between the top-down hypothesis and detailed bottom-up calculations will be reviewed.

5.1.1. Methodology

The chosen structure of splitting the upfront carbon on the different LCA modules, A1-A3, A4, and A5, can be considered the optimal way. When studying similar calculations, either EPDs or LCAs of buildings, this is usually how the results are presented. These particular modules can be traced back to EN 15978:2011, which shows the importance of established ways of performing an assessment. Structuring the calculations and presenting the results according to EN 15978:2011 enables easy analysis of the contribution of each module. Furthermore, it provides the possibility to compare the results with other projects to study whether the obtained splits are reasonable.

Moreover, splitting the results into various elements and materials for construction makes for easy analysis of elements and materials heavily affecting the upfront carbon. From a mitigation perspective, this allows a possibility to find suitable abatement strategies by analysing where the majority of emissions occur, which will be discussed later on in section 5.3. However, the focus of the following paragraphs will be to discuss the methodology of each module on a more detailed level.

A1-A3

When it comes to the methodology of actual calculations, the breakdown of formulas and structure presented in section 2.2.1 was intuitive to use. However, the possibility only of using generic emission factors is something to be discussed. While generic values often can be found in databases, they are, in fact, averages of a large set of data for the same type of material. Breaking down systems such as HVAC into the input materials would be the go-to strategy to define its upfront carbon. However, unfortunately, it might not be possible given the available knowledge and data in the early days of a project. Before commencing construction, specific systems and building elements might not be fully defined. This was the case when determining the Boden upfront carbon. Therefore, in the absence of generic data points, reference LCAs had to be used to determine the carbon footprint of systems such as HVAC. Similar problems occurred for various materials, where emission factors from EPDs had to be used instead of generic values. The problem occurring due to this is that the system or material found in the specific cases might not wholly match the ones to be used. The use of EPDs at this early stage can cause a misleading and false contribution of that material or system. However, using similar strategies should be considered instead of excluding the material. Since it could contribute to a source of error, emission factors should continuously be updated when more detailed information is obtained.

Furthermore, uncertainties such as those discussed above are inevitable when calculating the upfront carbon at the early stages. Therefore it is crucial to conduct an uncertainty analysis. The importance of this is discussed and covered in section 5.1.4. Other sources of uncertainty are that the explicit type of material might not have been entirely determined even where generic emission factors have been used. To exemplify, even though generic emissions factors have been used for a specific material, they might be emissions factors for the wrong type of concrete strength, the wrong structural steel, or the wrong thickness of sandwich walls. In this case, the "worst-case" concrete strength class has been assumed to be used everywhere. Since this is contradictory to the problem discussed in section 5.3, it further implies the need for uncertainty analysis while also raising awareness of the importance of updating the emission factor along with the timetable of construction.

A4

Regarding the transport, A4 emissions, the strategy to base the calculations on the equations in section 2.2.2 was deemed the best. Converting material quantities to weight and relating it to an emission factor considering both distance and total weight to be transported can be considered the most straightforward way of including all emissions occurring due to transport. Other strategies that can be considered are, for instance, the one found in the supplier information form found in appendix B. The supplier information form requests the total number of round trips, distance per round trip, and fuel efficiency. The three parameters yield the total fuel usage, which then can be related to an emission factor for the used fuel. The two strategies differ because suppliers are likely to know their transport distances, modes, and fuel efficiency. Thus more detailed calculations can be conducted. However, these parameters were more difficult to obtain for the thesis project. Therefore, it was simpler to relate the total weight of each material to a transport emission factor based on weight and distance.

Furthermore, one source of error important to consider is the actual distances. As the construction is yet to begin, the suppliers are not completely set. Thus, using 100% correct transportation distances is not possible. Therefore, it is crucial to find reference values that can be used, which was the case when calculating the A4 emissions for the Boden project. As mentioned earlier, standard distances were found and modified according to table 3.2. Although these still are assumptions, they allow for comparison with other reference projects and enable the possibility of finding strategies to mitigate transport emissions. Again, the various inaccuracies caused by assumptions further imply the need to conduct an uncertainty analysis. Furthermore, the used emission factors for road and sea freight were extracted from a UK source, which could have a negative impact on the A4 associated emissions, but most probably an insignificant effect on the total upfront carbon.

A5

Deriving and determining the contribution of module A5 to the total upfront carbon proved to be quite tricky. Because of varying methodologies, all including different parameters, one correct way was challenging to define. The chosen methodology is based on the regulations of climate declarations. This choice was motivated best because it enables some degree of comparability to other Swedish construction projects. Here, one source of error occurs because of the exclusion of transport of waste away from the site. The excluded contribution might not heavily affect the total upfront carbon, but it might have to be included in the future to achieve more detailed calculations. However, other inaccuracies would occur due to unknown distances between the construction site and waste disposal and handling areas, leading to further assumptions.

Furthermore, the used waste factors might differ from reality, which could significantly impact the final upfront carbon. Certain waste factors were extracted from the climate database provided by the National Board of Housing, Building and Planning, which can have a relatively high degree of confidence. However, where assumptions were made, the degree of confidence decreased. To increase the confidence level throughout construction, there is a need to collect waste data and update the assumptions when more detailed values are obtained.

Other possible sources of error regarding the emissions entailing construction and installation activities are those due to on-site fuel and electricity use. The used scenarios of 5.2 l/m2 and 43 kWh/m2 are estimates from One Click LCA, which might not apply to large-scale industrial facilities such as the one H2GS are to construct. However, the usage factors could both increase and decrease depending on the construction efficiency. Furthermore, the calculations regarding fuel emissions assumed that diesel would be the primary fuel for on-site construction activities. There is also a chance for it to be either bio-fuels or electricity. It is also important to consider the positive aspect of the green electricity available in the north of Sweden. Even if the electricity consumption is higher than the scenario, the subsequent emissions might not increase depending on where the electricity is sourced.

5.1.2. Evaluation of the hypothesis

The following section compares the first hypothesis, the top-down, upfront carbon, with the bottom-up calculations based on the full thesis scope, thus including all equipment and machinery.

With the Boden project being in the early phase, the chosen methodology of defining and deriving the upfront carbon can be deemed effective. By first approximating the upfront carbon with a top-down approach, one can obtain a plausible figure for the total carbon footprint. The hypothesis can then be used as guidance throughout the sequential bottom-up approach, which, as in the case presented in the results, might turn out different than the hypothesis. However, differences are expected since both the top-down and bottom-up calculations, to a certain extent, are based on assumptions with varying degrees of confidence. Furthermore, the difference can depend on more than the assumptions. An important aspect to consider is that the top-down approach, first-hand, is based on benchmarks for buildings such as offices, residential buildings, schools, and other public buildings. Because of all the heavy equipment and machinery that is to be installed in Boden, there is a significant need for heavy structural frames and high-strength concrete with reinforcement throughout the construction. Using high strength materials might not be the case for the benchmark studies used in the top-down hypothetic upfront carbon. The demands for extra structural strength and reinforcement will increase the upfront carbon of the H2GS site compared to the chosen benchmark buildings. With the use of benchmarks of buildings and facilities more comparable to that of the H2GS production site, the difference between the two approaches would be smaller. However, due to the scarcity of such studies, the chosen case studies had to be used for benchmarking instead.

Other than the dissimilar natures of the H2GS site and the building types used for benchmarking, a significant difference lies in the fact that the H2GS site comprises a multitude of different buildings. All the buildings situated within the site boundaries have a varying structural demand, and thus a large discrepancy between the upfront carbon of the various buildings is to be expected. A more accurate final upfront carbon could have been obtained by analysing each building one by one and adding them together at the end. However, due to the scarcity of exact data, the calculations for the bottom-up upfront carbon were performed as if the entire site was one building. Another critical factor that caused this source of error was the limitations of time. To conduct calculations and analyse the upfront carbon of each building would be highly time-consuming and challenging to do within the given time frame of five months.

It is important to keep in mind which phase H2GS is in regarding construction. When conducting similar calculations before commencing construction, a 100% accurate result is not to be anticipated. However, as noted in section 2.1.2, the earlier measurement is begun, the earlier management, meaning the implementation of mitigation strategies, can be put in place. This topic is discussed later in section 5.3.

5.1.3. Bottom-up approach

In the following sections, the results from the bottom-up approach will be discussed and reviewed. The results will be discussed by relating the Boden upfront carbon to benchmarking. Comparisons between the full scope and the climate declaration scopes are also presented. Finally, this section further highlights the importance and benefits of commencing similar calculations at an early project stage.

A1-A5 comparison

Comparing with benchmarks

Looking at the results from figure 4.3a, the splits are accurately showing a great majority of emissions pertaining to A1-A3, while A4 and A5 are somewhat equal. The acquired splits are to be expected, and match benchmarks found well. However, as can be seen in figure 4.2, A4 is quite significantly smaller than for the Boden case. Module A4 being smaller for benchmarks could be a consequence of the immense amounts of both concrete and steel that is to be transported to Boden, as well as large volumes of multiple other heavy construction materials and equipment. Furthermore, the transport distances are based on assumptions for a vast majority of materials and equipment. With further refinement and updating of distances as suppliers are decided, the obtained share for A4 of 6% could decrease. Furthermore, diesel has been the assumed fuel for all transport by truck. Electricity from renewable sources and sustainable HVO100 could be used to bring A4 emissions down.

Regarding A5, it is interesting to study the differences between the composite frame benchmark and the H2GS Boden facility. Here there is a difference of 3 percentage points. One probable reason for this discrepancy is their assumed electricity consumption of 50 kWh/GFA during construction and installation activities, compared to the assumption of 43 kWh/GFA in Boden. The assumed electricity to be consumed while constructing the plant will likely be higher than 43 kWh/GFA, which would increase module A5 emissions. Furthermore, the case study is performed on a construction project in Australia.

Assuming the electricity emission factor to be the average Australian energy mix of 0.656 kgCO_2e/kWh in 2020 (Tiseo, 2021), which is about 17 times higher compared to the one presented in table 3.4, this of course also yields increased module A5 emissions.

Full scope vs. climate declaration scope

For the splits on modules A1-A5 in the full scope and climate declaration scope, there are no drastic differences. This is interesting since a lot of materials included in the full scope have been excluded from the climate declaration scope. Equipment and materials pertaining to various on-site functions such as piping and plumbing, compressors and storage tanks, and water treatment are therefore not accounted for in the climate declaration scope. But still, the splits are somewhat equal. This was, however, not unsuspected since the emission factors for construction materials generally are that much higher than those entailing activities in A4 and A5. However, included in some of the excluded materials and equipment are more structural steel framings, such as pipe racks and skid constructions for storage tanks. Whether or not this should be included in the climate declaration scope is a point of discussion. Since the structural steel pertaining to these pieces of equipment would not exist if the actual equipment would not be installed, then including it for possible benchmarking would be a basis of misleading information. Therefore, it can be deemed reasonable to exclude the extra structural steel as well.

Material split comparison

Comparing with benchmarks

It is difficult to find a reasonable ground for comparison between the studied benchmarks and the actual results from the materials split in figure 4.3b. First of all, figure 2.2 shows the embodied carbon, not upfront carbon, of various construction materials. That fact limits the comparison to a certain extent. Still, since upfront carbon represents a large share of embodied carbon, a high-level comparison can be deemed possible. Furthermore, because all the steel plant-specific machinery and equipment are included in the thesis, there is a natural discrepancy limiting comparisons. As can be seen in figure 2.2, there are a few more materials not accounted for in figure 4.4b. The climate declaration scope did not include materials such as glass, windows, and doors because no such materials were identified in the cost estimate used as the source for quantities. Therefore, updating the calculations to enhance accuracy is essential as more detailed information on used materials and their quantities becomes available. However, comparing figures 4.4b and 2.2 accurately point to what primary bulk materials account for the most significant upfront carbon, namely steel and concrete.

Furthermore, materials such as "insulation" and "other metals" found in figure 2.2

have been identified but were included in certain construction elements and equipment rather than split into materials. For example, many walls were assumed to be sandwich elements with steel sheets surrounding insulation. Therefore, in figure 4.4b insulation is included in "external walls". More granularity might be desirable; hence a more detailed split on materials should be performed in the future.

Full scope vs. climate declaration scope

The materials included in the full scope and climate declaration scope differ dramatically. Thus, the final footprint of the climate declaration scope is around half of the full scope upfront carbon. Trying to limit the full scope to what should be included within the scope of a climate declaration proved difficult. What is usually included and excluded can be found in table 2.2. From that table, only load-bearing structures such as steel framing, foundational concrete and external walls were identified and included within this scope. Pilings, both concrete and steel, were excluded. The reason why the climate declaration scope was included was for future benchmarking with other Swedish similar large-scale industrial construction projects, even if climate declarations for industrial facilities are voluntary. Using the climate declaration framework as a basis ensures that the exact same materials and equipment are included, thus reducing the risk of erred comparisons. However, for the results to be effective, there is a large need to update the input to the climate declaration scope calculations as more materials are identified and quantified.

Benefits from early stage calculations

As previously discussed, there are many sources of errors associated with commencing calculations of upfront carbon at early stages, such as the case for this thesis project. Again, it is important to stress the fact that a 100% accurate calculation is not to be anticipated and that that should not be a deterrent. By putting the time in to try and do the very best one can do, there are a lot of upsides from a climate perspective. There is a large need for similar calculations to become more widespread and for the knowledge of the prevalent problem of upfront and embodied carbon to reach the public. In many ways, when conducting similar calculations before commencing construction, the final number derived is not the most important part. It is how businesses and corporations, after calculations try to decrease it. As stated in the first paragraph of the 1, there is a need to measure, learn about, influence and manage all types of emissions. Having conducted this thesis, all that is left for H2GS is to influence and manage the upfront carbon of their soon to be constructed facilities in Boden. It is, however, crucial for other businesses to follow in the footsteps of H2GS and try to measure, learn about, and mitigate their own upfront carbon. Together we can bring the problem of upfront carbon up front and make the buildings and construction industry a net-zero emitter.

5.1.4. Sensitivity analysis

The parameter uncertainties were modelled and quantified using a Monte Carlo model for the uncertainty analysis. The methodology uncertainties and model uncertainties, however, were not quantified. The methodology uncertainties associated with the system boundaries are relevant in this project. The system boundaries of the whole project scope cover a broader range of items and activities than benchmarks conducting a building LCA according to EN 15978:2011. The uncertainties arising due to this way of modelling are definite. No framework was used for the widened scope, and no projects found can be used to benchmark the results correctly. The lack of comparability leads to a high level of methodology uncertainty, which is important to consider when reviewing the results. The model uncertainties are entitled with, e.g., all the simplifications a project of this kind is using. The simplifications are many, and together they are likely to accumulate a large error in the calculations and results. However, although the final figure might not be a direct reflection of reality due to the range of uncertainties, the splits on LCA modules and materials may remain valid.

The Monte Carlo model imported most likely values from the primary excel model used in the bottom-up calculations. A triangular distribution was chosen because of the limited sample data available for each variable. By setting a lower and upper case in relation to the most likely value, only three data points had to be determined for each variable to create a distribution. In a more advanced and sophisticated analysis, an extensive range of samples could generate the distribution for each variable. The model ran 8000 simulated scenarios based on the triangular distributions of each variable. It is possible that the precision of the model would increase with an increased number of simulated scenarios.

Looking at figure 4.5, the offset to the right of the base-case 1 is clear. The offset is explained by the variables' non-uniform distributions, which in most cases were in favour of the upper case. The results show that the mean value of the 8000 simulations was 3.9% higher than the base case calculated in the bottom-up calculations. The mean indicates that a higher upfront carbon is likely than the one calculated in the bottom-up calculations. In the worst case, the Monte Carlo simulation results show that the total upfront carbon can be 16.3 % higher than the base case, while the best case would be a decrease of 5.7% compared to the base case. The total upfront carbon for the 5th percentile is 0.991 compared to the base-case of 1, while the 95th percentile is 1.091. The range between the two percentiles accommodates 90% of the samples and is more representative of the probable outcome than the extreme values. The 95th percentile means that while the extreme case is an increase of 16.3% compared to the base case, only five per cent of the modelled samples exceeds an increase of 9.1%.

While figures 4.6 and 4.5 shows the results from the Monte Carlo simulations to the total upfront carbon, 4.7 shows the relative contribution for the top drivers of uncertainty. Unsurprisingly, these are contributions from LCA modules A1-A3. Generally, the main building materials, structural steel and foundational concrete, contribute considerably to the uncertainties. Apart from the building materials, it is also visible that the process equipment has a high contribution to the uncertainty. The tornado chart shows results that remind of the ones in figure 4.3b. The tornado chart shows the contribution of the 5th and 95th percentiles from the simulations rather than the base case. The results from figure 4.7 can help identify what variables one should focus on to reduce the total upfront carbon. The top drivers are, in the majority, items that are outside the scope of EN 15978:2011. This implies a high potential to decrease the total upfront carbon from the construction of an industrial site by widening the scope from only looking at the buildings themselves.

5.2. Plug- & Play model

With the plug- play model extracting a vast majority of its data directly from the Boden upfront carbon calculations, there are some areas of concern regarding emission factors for all LCA modules. First off, many of the emission factors for the largest bulk materials, such as concrete and steel, has been sourced from the climate database provided by the Swedish National Board of Housing, Building and Planning. These emission factors may be generic but might still best be applied to construction materials manufactured and used for construction in Sweden. With the tool being constructed with the purpose of calculating embodied carbon for a new hydrogen production facility, perhaps located anywhere in the world, this is a possible source of error. The best solution to this problem would probably have been to use worldwide generic emission factors. This would, however, have meant a total reconstruction of the emission factors used in the Boden calculations, therefore making it time-consuming. Regardless, this source of error should be kept in mind for future refinement of the scalable tool.

Furthermore, as it comes to transport distances used for a majority of the materials that are extracted from the Boden calculations, they are based on sea freight across the Baltic Sea. The three transport legs are as well based on how materials are assumed to be transported to the Boden site. Shipping by both sea and road might not be applicable everywhere in the world. However, creating a tool able to generate generic transport distances based on chosen new location could very well be the scope of its own master thesis.

When it comes to possible sources of error in module A5, chosen waste factors come to mind. Like with emission factors for multiple construction materials, these were sourced from the climate database provided by the National Board of Housing, Building and Planning. Again, these might be more applicable to construction waste scenarios in Sweden. Other countries could possibly have come either longer or shorter than Sweden regarding recycling construction waste. Whereas waste is a major factor in module A5 emissions, electricity use could as well have a large impact on the upfront carbon. With

Sweden having such clean electricity, this is not as apparent as it would be in, e.g., China.

Another aspect to consider is that, as aforementioned, a majority of the data used in the scalable tool are based on the Boden calculations, which to a certain degree is based on early estimates. With the Boden construction yet to begin, factors such as material quantities, transport distances, electricity consumption and waste rates are all, to a certain degree, assumptions. Once the Boden construction is finished and the upfront carbon calculations for it are updated, the accuracy of both the Boden facility and the plug- play model will increase.

All the factors presented above make it difficult to assess the accuracy of the plug-play model for worldwide use. However, it is important to again discuss the matter of expecting a 100% accurate result. Again, the model is intended to be used as early as during feasibility studies, where no suppliers have been selected and maybe even before any type of engineering has been made. To have the possibility to identify possible carbon hotspots that early makes for a great possibility to manage and influence all upfront carbon. Looking back at figure 2.5, this tool is to be used at the top of that slope, where all mitigation strategies covered in 2.6 are possible options. Therefore, although the tool might need further refinement and updating once reference values from Boden are more accurate, the tool itself may come very much in handy already.

5.3. Carbon mitigation strategies

Out of the 12 upfront carbon mitigation strategies presented in theory section 2.6, four were quantified in the analysis shown in the results section 4.3 with the same title. These particular ones were chosen based on the point of time the analysis was made. Some of the presented upfront carbon strategies in the theory section are virtually impracticable based on where in the construction timeline H2GS are currently. A mitigation strategy such as the third one, “Reuse existing substructures”, can greatly affect the overall upfront carbon. However, this must be considered during the feasibility study of potential sites. Particularly for a steel plant, the reuse of existing substructures may be very hard to realise. The three mitigation strategies with the highest potential are considered to be climate improved concrete, scrap-based steel and avoidance of over dimensioning. The reinforcement steel was not further analysed because the rebar used for construction in Sweden is often made of a high content scrap already today. The high scrap content of rebar means that this mitigation strategy should be realised for most projects in Sweden already. This strategy is yet considered to have a large potential to reduce the upfront carbon due to the large amounts required to reinforce the concrete. If a rebar type with a lower scrap fraction and a higher fraction of virgin iron is used for manufacturing, the overall upfront carbon increases significantly.

Based on the available data at the time of the analysis, quantifying the mitigation strategy “avoidance of over dimensioning” was challenging, which is why no such quantification was made. However, the mitigation strategy may very well apply to the H2GS Boden project. The steel frame may be over-dimensioned, and effort could be put into excluding redundant structural steel. To make an example of how the buildings industry could be affected by decreasing the redundant steel, the case studies from section can be used to perform a “back of the envelope calculation”: Per numbers from 2006, there were 290 Mt of steel allocated to the buildings industry worldwide (Moynihan and Allwood, 2012). Assuming that the findings from the case studies (i.e., that the average utilisation rate of construction steel, when weighted by mass, is 54%) are applicable on the entire buildings industry, meaning that 46% of all steel in buildings worldwide is unnecessary, that results in a total of 133.6 Mt of redundant steel per year allocated to buildings. According to Moynihan and Allwood (2014), an increase of the utilisation rate by 36 percentage points (from 54 to 90%) is reasonable. The increase in utilisation means that the redundancy would be decreased to 10%, which yields total savings of 104.4 Mt steel per year. From a carbon emission perspective, using a generic emission factor of 2.56 tCO_2e/t steel, that implies a yearly abatement of ~267 $MtCO_2e$, more than double of Finland’s and Sweden’s total CO_2e emissions from 2020 (48.1 and 49.7 $MtCO_2e$, respectively) (Statistiska Centralbyrån, 2021; Statistics Finland, 2022).

To the optimisation of reinforced concrete usage, the overall upfront carbon could be reduced by assessing what type of concrete is needed for each area on the site. Using the lowest strength possible also means that there is no room for future redesign or reuse depending on the requirements of the foundation’s strength at a future time. Designing for a minimum strength could potentially even harm the whole life carbon. This is one example where solely assessing the upfront carbon have disadvantages compared to a whole life assessment.

Increasing the use of modular and prefab sections and domestically sourcing of materials are two mitigation strategies that can help reduce the upfront carbon. However, in this particular project, the potential is not high enough to be compared to the four strategies presented in the results. The lacking potential does not mean they are not worth investigating, as every type of reduction is good.

When analysing figure 4.8, it is important to keep in mind that the presented results are directly linked to the assumed base-case design. The upfront carbon in this project has to the highest possibility been assessed using generic data that might end up differing from reality. That means the results from this analysis are highly hypothetical. According to 4.8, structural steel has the highest potential of reducing the overall upfront carbon in this project. This assumes that structural steel made of virgin iron with a generic EF based on industry averages is used in the base case. The width of the structural steel bar in figure 4.8 also shows that the structural steel makes up for a larger part of the upfront carbon in the base case than the three others, while the height shows that the potential reduction in upfront carbon to structural steel is 64% which is explained by the change of EF. The ready-mix concrete has relatively high addressable emissions, while the height of the bar shows that the potential of lowering these are limited. The limited potential to decrease the EF of concrete results in a fairly low overall reduction of the upfront carbon. However, this is based on the Climate Database provided by the National Board of Housing, Building and Planning', which is a database built from generic industry averages. The generic data means some suppliers can deliver concrete with both higher and lower EF than the generic value. Considering the addressable emissions of concrete to be high, a small increase in the relative reduction of concrete (i.e., the height in the graph) to the upfront carbon can have a high impact on the total reduction of upfront carbon. Hopefully, with further research GGBS, FA and EAF reducing slags can all be increasingly exchanged for cement in the future. An alternative way to reduce the EF of concrete is to reduce the climate footprint of cement itself, which could be realised by further research within CCS and CCU.

The two last mitigation strategies in figure 4.8 are alternatives where traditional energy sources are exchanged with renewable ones. In the case where sustainable transport measures are used to exchange diesel with HVO100, the potential reduction to the overall upfront carbon was 2.4%. The reduction could be further improved in the future by driving on fully renewable battery electric vehicles or fuel cell electric vehicles together with net-zero sea transport. In this case, the height of the purple bar would effectively increase to 100%, and the total reduction in upfront carbon would increase to 4.2%. Finally, exchanging traditional energy sources on the construction site with renewable ones is the mitigation strategy with the highest relative reduction. Since the addressable emissions are relatively low, especially in relation to the three other ones, the total reduction to the upfront carbon is no more than 0.7%. The total upfront carbon in the base case is, however, as previously discussed, based on a scenario on average energy and fuel for a construction site in the Nordics. Considering the whole project scope in this project includes more than the scenario considers, the addressable emissions are likely higher in reality.

From the presentation of the discussed mitigation strategies, the perception might be that there is no reason not to implement them. However, as with any change to traditional working methods, challenges may arise. Many of the strategies might mean that an increased effort in project planning and engineering is needed to realise the project. Most notably may be a potential increase in cost associated with the building element or construction process. The cost, which in most projects is a vital variable, is a dimension that has not been considered in this analysis. It should be noted that specific mitigation strategies, such as building optimisation, can have a positive impact on both CO_2e and cost. There are also mitigation strategies that do not necessarily need to increase the project's cost, such as construction steel made of high-content scrap. However, while the material cost of certain materials does not necessarily increase the cost of the project itself, costs associated with activities such as additional engineering might arise. To prioritise what strategies to implement in a project, a matrix could be used to map out the potential savings of CO_2e in relation to the associated cost. Figure 5.1 shows an illustrating example of how such a matrix could be used. The potential

CO_2e abatement is illustrated on the x-axis while the y-axis represents the associated change in cost. Each bubble represents a possible way of reducing the upfront carbon. A vast increase in cost is needed in the red areas compared to the baseline scenario, while the green areas showcase mitigation strategies that have low or even negative costs associated with them relative to their carbon savings. The figure also illustrates how a high price can be more motivated by a higher relative CO_2e abatement than for a lower one.

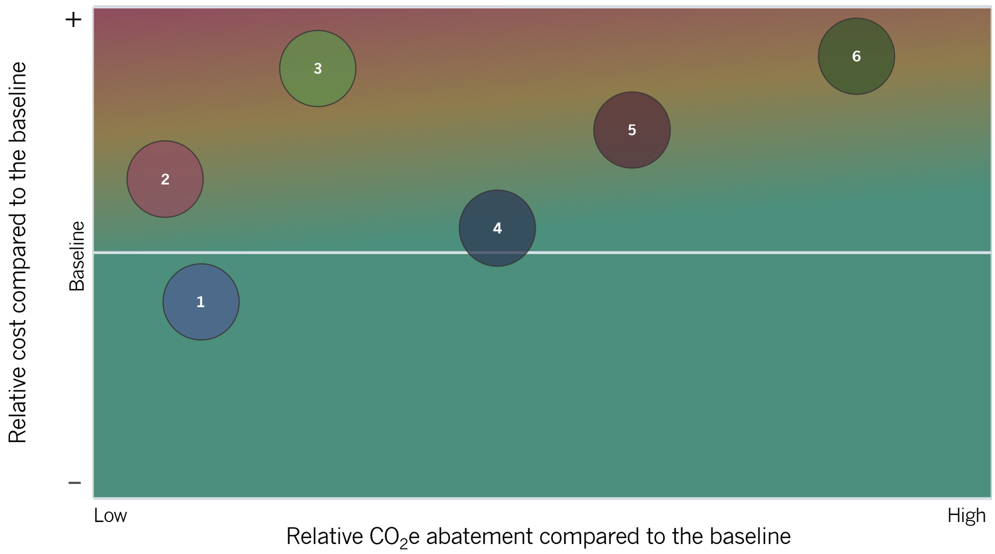


Figure 5.1.: Bubble-chart showcasing how mitigation strategies can be put in relation to cost

5.4. Supplier comparison and evaluation

The supplier evaluation and comparison sheet that was developed for the RFP is one way to enhance the possibility of assessing the carbon footprint from the construction of the industrial site. This document's most influential design criteria was to keep the calculations as simple as possible. It was concluded that the more accessible the paper and associated tables were to fill in, the higher the response quality. However, this design criteria meant some simplifications of calculations were necessary. As the alternative to conducting calculations is to supply EPDs that are already in place, there will likely be a mix of EPDs and simplified calculations. Having a mix of EPDs and estimates using generic data means the actual outcome is not directly comparable. However, the level of detail and effort put into the calculations can signify how aware and interested the supplier would be in finding alternative ways to reduce their contribution to the overall upfront carbon. The calculations also show the estimated material quantities, method of transport, fuel use, and waste rates, which can be compared.

Moreover, a supplier with already available EPDs signals they are already aware of the importance of assessing the carbon footprint of their products. The scope of this thesis did not consider exactly how the figures should be compared systematically, which is a subject for future work. The results from the Boden calculus will, together with the response from the supplier evaluation and comparison sheet, enable the possibility of comparing suppliers from a sustainability perspective to some extent. Furthermore, the response from the RFP can act as a ground for setting demands on the suppliers to decrease their baseline emissions. This way, the contribution of upfront carbon from the suppliers can be measured, managed and influenced to decrease.

5.5. Downstream value of upfront carbon assessments

With the calculations having been performed, many hard values had been covered. There was, however, a need to evaluate softer values as well. That very need was why the thesis set out to explore questions and opinions from stakeholders, such as what perceived value and importance they find in it. The findings were exciting and pointed to a value in performing similar calculations. From the customer perspective, it can be said to bring the most value in the early stages, such as right now. The importance, however, lies in how the message is communicated. Before commencing operations, the construction emissions, i.e., the upfront carbon, are the largest source of emissions. Therefore, it can be crucial to know this footprint. However, the actual value seems to lie in the company's efforts to mitigate the emissions. Communicating and taking action on developed abatement strategies can be a great selling point for a company and thus increase value for both parties.

Conducting similar calculations is, as of right now, voluntary. It is, however, not chocking that both the Swedish Environmental Protection Agency and the National Board of Housing, Building and Planning find it positive for companies to take action on all possible areas of emissions. With upfront carbon becoming a more and more prevalent problem, it is necessary to not only do what is mandatory. Furthermore, with the regulations of climate declarations set to expand, industrial facilities may be required to perform climate declarations. It is also possible that a broader range of materials and equipment may become mandatory to include. Therefore, with H2GS already having conducted one, they are in a great spot.

Chapter 6.

Conclusion

This project was centred around five research questions together with a problem statement. Throughout the assignment, the term upfront carbon has been the keyword and has served as the common factor. The idea of all tasks performed has been to enable the possibility to measure, manage, influence and learn about the carbon footprint. The following section is a reflection on the conclusions of the five research questions.

Q1. What are the potential CO_2e emissions during the construction of the H2GS large-scale industrial project in Boden, including the construction process, construction material and process equipment?
A widespread standard for calculating construction emissions is found in EN 15978:2011. In this project, the standard has been used throughout the scope, both directly and indirectly. The standard itself does not give any excessive tools for calculating the contribution to the whole life carbon in each LCA module and instead focuses on how such an assessment should be done and what it should contain. Sources such as One Click LCA and the National Board of Housing, Building and Planning have been used to learn about the actual calculations. Since the purpose of this assessment was to include the process equipment apart from the construction process and materials, the standard had to be used as inspiration rather than strict calculation rules. The anticipation of this research question was not to conduct a LCA, which in line, has not been the case in this project. An assessment has been made where the results show the possible upfront carbon, i.e., the potential CO_2e emissions during the construction of the H2GS large-scale industrial project in Boden. The result shows how the upfront carbon is divided on LCA modules A1-A5 and by material categories. A Monte Carlo simulation has been made to treat the parameter uncertainties associated with the calculations, which shows that it is probable that the calculated upfront carbon in the bottom-up approach is likely to be higher in practice.

Q2. How is a plug- & play model allowing comparisons of CO_2 construction emissions for a hydrogen plant depending on the equipment used and size of equipment best implemented?
The plug- & play model was eventually developed as an extension of the model created to answer the first research question. The way of reusing the results from the Boden

project was considered the best way of implementing such a model. By accessing an already functioning tool, rescaling another physical quantity, the rescaling mechanism did not have to be reinvented. Instead, most of the effort was put into integrating the carbon calculations into the existing model and evaluating whether or not the scaling applied to the carbon footprint.

Q3. How can the model be used to recommend materials & best practices H2GS can apply to decrease CO_2e emissions?
From a large set of mitigation strategies, nine were further researched and proposed as possible ways to decrease CO_2e emissions. The model, i.e., the excel-model used for research question one, was used to confirm the findings on mitigating the construction's carbon footprint. The mitigation strategies were categorised as building optimisation, climate-friendly energy sources, and climate-improved materials. While a few of these recommended materials and best practices are impracticable for the Boden project, they could help H2GS in their mission to decrease CO_2e emissions in future projects.

Q4. How can the master thesis supply input to CO_2-supplier comparisons/evaluations and demands on supplying partners?
The most fitting way to compare and evaluate suppliers was considered to be as part of the RFP. A document was produced through several iterations with the focus based on the supplier's estimated contribution to the overall upfront carbon. The received data from the potential suppliers can both be compared to the calculations used to answer research question one, and to each other. Furthermore, with knowledge of the upfront carbon, targeted limits and mitigation strategies in the form of demands on the suppliers can be developed.

Q5. What is the downstream value of assessing the carbon footprint from a construction project?
To evaluate the value of performing upfront carbon calculations, the team sent questionnaires to stakeholders outside the organisation. Considering the softer values was important to assess whether customers and public authorities saw a purpose in similar work. The questionnaires made it clear that the importance lies in how the results are communicated. All actions on emission reduction are essential, mandatory and voluntary. Furthermore, even if the regulations of climate declarations today exempt industrial facilities, there is reason to believe that they will become included within the law in the future. Thus, having had this thesis conducted, H2GS are in a great spot looking forward.

Chapter 7.

Future Work

Based on the set timeline and amount of time available for this project, only so much could be included in the scope. Calculations of the upfront carbon, ways to assess the hypothetical upfront carbon faster in future projects, and how to mitigate the emissions have all been the focus of this thesis. Many concepts and ideas that have been disregarded due to time constraints have been discussed during the project. Besides, some things cannot currently be accomplished because of the current timeline. Some of the most relevant and important ideas and concepts are suggested as acts for future work.

7.1. Follow-up

First and foremost, this thesis has developed the groundwork for several opportunities that can be further developed and followed up as the project proceeds. Considering the point of time this project has been carried through, there is a need for follow-up. The following sections propose ways of how the scope of the thesis could help excel further in the topics of upfront carbon.

Defining the upfront carbon

The data inventory of this project has primarily been based on cost estimates, assumptions and know-how from colleagues at H2GS. As the project proceeds, the available data will be of higher quality, and the preferred usage of data, according to table 2.1, will be different from today. This means that while this thesis has set up the hypothesis of the potential upfront carbon entitled with the construction, the data must be updated continuously. This follows the process explained and illustrated in figure 2.3. The design philosophy of the model was always to make it as easy and well-structured as possible, enabling easy refurbishment of data.

Plug- & play model

For the plug- & play model, the same way of thinking as for the upfront carbon model should be adopted. As the construction project of the steel plant in Boden proceeds and eventually is finalised, the data used for the plug- play model can be updated and better reflect reality. In the future, when more projects have been completed, a more extensive set of data for various production requirements and geographical locations may be available. This will enable a better and more sophisticated plug- play model that can be used to compare CO_2e construction emissions depending on the equipment used and its size.

Carbon mitigation strategies

Just as for any construction project, there are demonstrated ways to mitigate the upfront carbon from this project. Future work in this area includes weighing the potential reduction of emissions savings in relation to the associated cost. Finding the most cost-effective mitigation strategies and delivering this message to the industry can help commence more initiatives to reduce the construction industry's carbon footprint. However, an increased cost may be necessary to really affect the upfront carbon. Weighing cost in relation to the carbon emissions abatement can help differentiate between high abatement low cost and high abatement high-cost alternatives quickly. The ability to affect could potentially be added as a third dimension to this model. This could be a measure helping where to put focus depending on the timeline. To exemplify the ability to affect, it might be more straightforward to exchange traditional construction steel with high content scrap structural steel than requiring all the manufacturers to use renewable fuel in their production process. While the low-effort alternatives may be the most accessible short-term, the alternatives requiring more effort could enable a more significant abatement potential over time when looking at the greater picture (i.e., affecting the upfront carbon of more projects).

Supplier comparison and evaluation

With the sustainable supplier information form in place as part of the RFP a lot of data will eventually be accessible. This data could, and should, be used to revise all assumptions made about the material types and quantities of the models developed in this thesis. Further work on how the exact evaluation and comparison should be made concerning the received data should also be developed.

7.2. Moving from upfront to whole life carbon

While this project's scope has solely been the upfront carbon, the whole life carbon has been regarded throughout the project. Optimising the abatement potential entirely to the benefit of the upfront carbon is of no value if it does not improve the whole life carbon. While the upfront carbon is important to mitigate to reach the 1.5-degree target, sub-optimisation must be avoided in the first place. This means that in future assessments, and when time allows, it is highly suggested that the whole life carbon is regarded rather than the upfront carbon alone.

7.3. Development of a refined methodology

In this project, an attempt to account for the complete carbon footprint of the construction within the boundaries of the H2GS production site has been made. Considering the timeline and the extensive number of items the project considers, the analysis has had to be relatively shallow. The results show that almost half of the calculated footprint originates from items outside the limits of the building materials. This calls for the importance of assessing these items as well. Although there are more limitations regarding material choices for items such as process equipment and material handling equipment than for building materials today, conscious choices of materials for certain items may be possible. Nonetheless, there is a need for a framework where buildings can be assessed together with the necessary systems and equipment-making up for a functioning facility.

Appendix A.

Interview guide

Potential customer

1. Have you conducted similar calculations?
2. What is your opinion on that your suppliers strive to reduce all company emissions?
   a) Is it possible that voluntary actions on mitigating emissions is valuable in your supplier comparisons and evaluations?
3. The thesis work might seem important internally, but as a customer, do you see any value in your suppliers calculating and mitigating construction emissions?
4. Do you think that similar work will increase in importance to reach net-zero?
5. is there any way for you to include mitigation actions by your suppliers in your own climate/sustainability reporting?
   a) Could it be included in your Supplier code of Conduct?
   b) Do you see any downstream value in your own value chain?

The Swedish Environmental Protection Agency

1. Do you find it common for large industries to calculate their construction related emissions?
   a) Would you assume embodied- and upfront carbon calculations and mitigation strategies to become more frequent and of growing importance to reach net-zero?
2. What is the reason for the exemption of industrial facilities in the National Board of Housing, Building and Planning's requirements of Climate declarations?

   a) Would you assume industrial facilities to be included in the future?

3. Are there any financial aids or other incentives for mitigating embodied- and upfront carbon emissions, such as a procurement of climate improved materials?

   a) If not, is this something that might become reality?

4. If and what value do you see in companies aiming to calculate and mitigating their embodied- and upfront carbon emissions, even though it might be voluntary?

The Swedish National Board of Housing, Building and Planning

1. Do you find it common for large industries to calculate their construction related, embodied- and upfront carbon, emissions?

   a) The requirements of climate declarations for new construction exempts industrial facilities. Why so, and are there plans for including such buildings in the future?

   b) Do you see an increase in the frequency of such calculations, but more importantly a growing importance in calculating and mitigating emissions for all types of buildings to reach net-zero?

2. Will the requirements for reducing emissions from new construction increase in the future, and as of today, are there any incentives for doing so?

3. What is your opinion on industrial companies voluntarily calculating and developing strategies to mitigate emissions from new construction?

Appendix B.

Example of a potential supplier emissions model

Sustainable supplier information form

Introduction

At H2 Green Steel (H2GS) we want to establish a sustainability mindset throughout the organization. As a driving force in Carbon Dioxide (CO2) abatement, it is important for us to know our total carbon footprint. We will calculate the total emissions from constructing our entire facility in Boden and as a contractor to us it is important that you share our ambitions of contributing to fight climate change. Therefore, we are asking you to provide information on what carbon emissions your services to us entail.

Emissions we will measure

The emissions we ask you to provide are the so-called Life Cycle Assessment (LCA) product- and construction process stage (A1 – A5) emissions, according to the standard EN 15978 (*Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method*). The full life cycle can be found in the figure below, where the emissions we are trying to capture are the "Upfront Carbon" emissions, highlighted by the red border.

The product stage (A1 – A3) emissions are the emissions associated with the **extraction** and **transport of raw materials**, as well as **manufacturing** of the product. In example, for steel the product stage emissions include those from breaking iron ore to the finished steel product.

Transport (A4) emissions are those occurring during transport of the product **from the manufacturing facility to the construction site**, e.g., by truck from manufacturer to the site.

The construction and installation (A5) emissions are those occurring due to construction site activities and waste generated on-site.

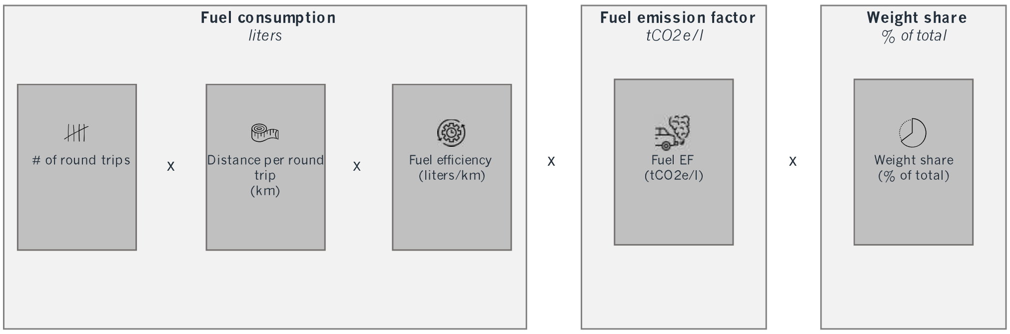
- Site activities include emissions from electricity use (e.g., from the local/national grid), as well as fuel use (e.g., consumed by construction machinery or diesel generator)
- The construction waste generated on-site is measured by a percentage of the delivered weight, and the recycling rate of the waste

For more information regarding the emissions, we ask you to provide information about, a comprehensive guide can be found in Appendix.

Transport (A4)

The transport emissions are calculated by estimating the emissions associated with the transport from the production facility to the construction site, as illustrated in the figure below.

Transport (A4) emissions for material Y
tCO2e



By multiplying the total fuel consumption by the emission factor of that fuel, the transport emissions are calculated. Emission factors for varying fuel types can be found in Appendix. Include the share of the total weight each transported material represent.

Example: transport emissions

Material	Share		# of round trips		Distance perround trip (km)		Fuel efficiency (l/km)*		Vehicle EF (tCO2e/l)		Total (tCO2e)
Concrete	83%	x	5	x	400	x	0.25	x	0.00269	=	~1.1
Reinforcement	17%	x	5	x	400	x	0.25	x	0.00269	=	~0.23
Packaging materials	A%	x	B	x	C	x	D	x	E	=	F

Note: Fuel efficiency fictional, use own. Emission factor sourced from Appendix Link 2g

Appendix C.

Details on the stages of a life cycle assessment

Use stage embodied carbon

The use stage embodied carbon is part of the embodied carbon but only refers to the carbon emissions from the materials and processes needed to maintain the building during the use phase. That means the use stage embodied carbon covers the use phase (B1), maintenance (B2), repair (B3), replacement (B4) and refurbishment (B5) (World Green Building Council, 2019).

Operational carbon

The operational carbon is not part of the embodied carbon and refers to the carbon emissions entailed by operating the building. That means the operational carbon covers the operational energy use (B6) and the operational water use (B7) (World Green Building Council, 2019).

End-of-life carbon

The end-of-life carbon is part of the embodied carbon but only refers to the carbon emissions entailed by dismantling and decommissioning the building. The end-of-life carbon is the carbon emissions generated after the building is used. That means the end-of-life carbon covers deconstruction (C1), transport to the end-of-life destinations (C2), the waste processing (C3) and disposal (C4) (World Green Building Council, 2019).

Beyond the life-cycle

The carbon savings from beyond the life-cycle (D) are carbon savings that can be made from recycling or reusing materials. Beyond the life-cycle carbon emissions can also be the use of the waste as a fuel source for other processes. That means the carbon savings beyond the life-cycle are neither part of the whole-life carbon nor the embodied carbon and its' subcategories (World Green Building Council, 2019).

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Interviews

Interviewee: Boverket (2022). The National Board of Housing, Building and Planning. Interviewed through e-mail questionnaire on 2022-04-12.

Interviewee: Customer (2022). Potential customer. Interviewed on 2022-04-07.

Interviewee: Landborn (2022). Alexander Landborn is the founder of ClimateWorks, a company offering different types of climate calculation services, internal training on how climate calculations work in practice, as well as inspirational lectures. Landborn has experience from multiple projects where the aim has been to reduce the carbon footprint of buildings. Interviewed on 2022-03-17.

Interviewee: Warmark (2022). Katarina Warmark, Climate Analyst at the Swedish Environmental Protection Agency. Interviewed through e-mail questionnaire on 2022-04-11.

Interviewees: Nyberg and Holmstedt (2022). Henrik Nyberg, Business Development Manager at IN3PRENÖR AB and Louise Holmstedt, Specialist Sustainable Development at Bengt Dahlgren AB. Interviewed on 2022-03-28.