Life Cycle Assessment of Portland Cement and Concrete Bridge

Concrete Bridge vs. Wooden Bridge

Marjan Mousavi

ROYAL INSTITUTE OF TECHNOLOGY

Master of Science Thesis
Stockholm 2013

KTH Industrial Engineering
and Management

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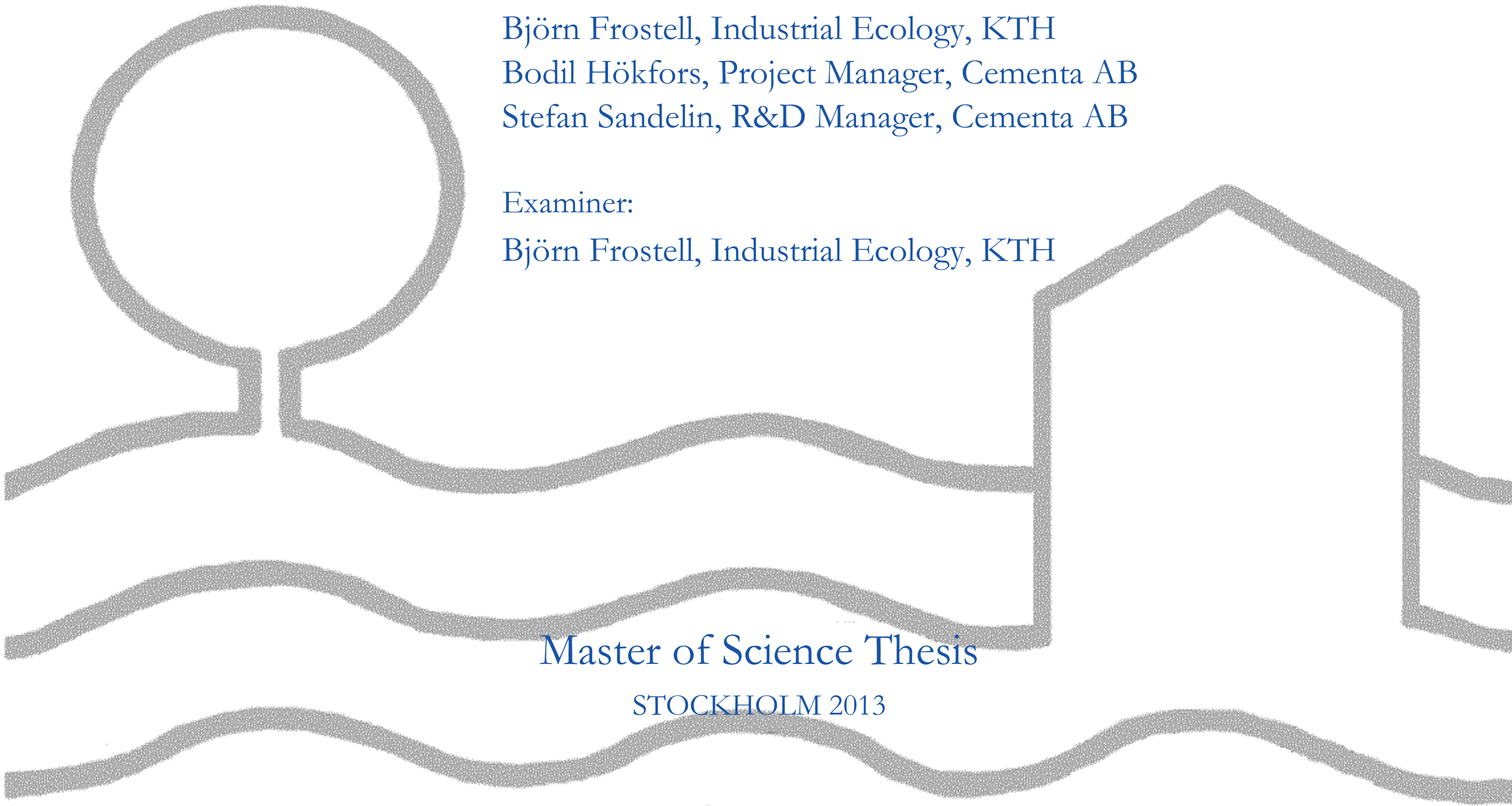
Supervisors:
Björn Frostell, Industrial Ecology, KTH
Bodil Hökfors, Project Manager, Cementa AB
Stefan Sandelin, R&D Manager, Cementa AB

Examiner:
Björn Frostell, Industrial Ecology, KTH



Master of Science Thesis

STOCKHOLM 2013

PRESENTED AT

INDUSTRIAL ECOLOGY

ROYAL INSTITUTE OF TECHNOLOGY

TRITA-IM 2013:09

Industrial Ecology,
Royal Institute of Technology
www.ima.kth.se

Abstract

Today global warming mitigation, natural resource conservation and energy saving are some of the significant concerns of different industries, such as cement and concrete industries.

For that reason, a streamlined life cycle assessment (LCA) model of one ton of a Portland cement, CEM I produced in Cementa AB's Degerhamn plant, has been developed by using the LCA software KCL-ECO. LCA is a tool that identifies in which stages of a product's life cycle the most environmental burdens occur. The environmental analysis was limited to identify total energy consumption and total carbon dioxide (CO_2) emissions per ton of Portland cement. Results show that the most significant energy consumption and CO_2 emissions are related to clinker kiln, due to the process of calcination of limestone and fuel combustion in the kiln. Of total CO_2 emissions, 52 % and 46 % result from the calcination process and fuel combustion respectively.

One of the applications of CEM I is in construction of concrete bridges. Therefore an LCA model of a concrete bridge located north of Stockholm was developed in KCL-ECO. Environmental indicators calculated are: total CO_2 emissions and energy consumption through the entire life cycle of the bridge. CO_2 uptake or carbonation of the concrete during the service life of the product and end of life treatment is one of the advantages of concrete products. During the carbonation process, some of the total CO_2 released from calcination will be absorbed into the concrete. Results indicate that production of raw materials and transports during the life cycle of the concrete bridge, are main contributors to total CO_2 emissions. Among raw materials, cement production has the highest CO_2 emissions. Energy consumption is mainly related to concrete and concrete products production. CO_2 uptake during the use phase of the bridge is small compared to total CO_2 emissions from calcination. Furthermore, the results show that different waste handling practises result in different CO_2 uptake behaviours. The total CO_2 uptake from crushing and storing of the demolished concrete (scenario 1) and landfilling of the demolished concrete (scenario 2) is 10 % and 5 % of the total CO_2 emissions from calcination respectively.

Since comparison of different construction materials from an environmental point of view is always desirable, the LCA tool was used to compare the total energy consumption and the CO_2 emissions from a concrete bridge and a wooden bridge. The functional unit was defined as 1 square meter of bridge surface area, since the bridges were of different sizes and shapes. In this comparison the total emissions and energy consumption were much higher for the concrete bridge than for the wooden bridge.

In order to show how different assumptions could affect the results, a virtual concrete bridge with the same shape and size as the wooden bridge was designed and compared with the wooden bridge. The functional unit selected for this case was one bridge. In this case the virtual concrete bridge requires less energy, while the wooden bridge emits less CO_2 to the atmosphere. For the wooden bridge, CO_2 in growing forests was included, which could be debated.

Overall, a comparison of the environmental performance of the wooden bridge and the concrete bridges was more complex than initially expected and great care is recommended in choosing material and application. With concrete, the design (and quantity of material used) seems to be a very sensitive parameter and may result in much larger energy used and CO_2 emissions than a wooden bridge. On the other hand, the virtual bridge comparison showed that concrete advantages such as higher durability and lower maintenance may be theoretically combined with a comparable energy and climate performance as a wooden alternative.

Key words: Life cycle assessment (LCA), cradle to gate, cradle to grave, functional unit, carbonation

Acknowledgements

I would like to express my sincere gratitude to my supervisor Ass.Prof. Björn M Frostell at KTH, for the continuous support of my master thesis. His guidance helped me a lot in writing this thesis.

I would like to acknowledge the academic and technical support of my supervisors at Cementa AB, Bodil Hökfors and Stefan Sandelin, and for their good pieces of advice and friendship as well, for which I am extremely grateful.

I owe sincere thanks to Håkan Stripple at IVL, who guided me through the whole process of writing the dissertation. I am sure that this dissertation would not have been possible without his truly helpful support.

In addition, I would like to show my gratitude to my family for their moral supports.

Stockholm, May 2013
Marjan Mousavi

Contents

1-Introduction

One of the composite construction materials that various constructions such as beams, dams, bridges and houses benefit from is concrete. However, it should be taken into account that production of this material inevitably has some drawbacks to the environment, due to greenhouse gas emissions and energy consumptions. Concrete is mainly made of aggregates, cement and water that cement production causes the largest CO_2 emissions; approximately 5 % of total anthropogenic emissions (WBCSD, 2002), and is one of the top two industries that contribute to CO_2 emissions (Van Oss and Padovani, 2003).

Over the last decades, it has been a great deal of burden on cement industries to lower these crucial drawbacks which leads to great achievement in this field.

Cementa AB within HeidelbergCement, as one of the cement manufacturing companies in Europe with highly developed technologies, has been trying to evaluate and improve cement's impacts on the environment. Cementa AB's Degerhamn plant as one of the first cement plants in Sweden focuses on manufacturing a Portland cement for heavy concrete constructions that has a low heat development.

Portland cement is one of the fundamental components of concrete and mortar. It is fine-grained powder made mainly out of limestone. Portland cement is a mixture of finely ground clinker, gypsum, and small amounts of chemical admixtures. There are three different groups of Portland cement: CEM I, CEM II, and CEM III, which are grouped according to their clinker content. CEM I has approximately 95-100 %, CEM II about 65-94 % and CEM III has between 20-65 % of clinker. Clinker content varies according to cement type, application area and the customer requirements.

In this thesis project environmental performance of one ton of a Portland cement, Anläggningscement (CEM I 42.5 N-SR3 MH/LA), produced in Degerhamn plant is evaluated based on total CO_2 emissions and energy consumptions. CO_2 emissions result mostly from clinker production, an intermediate product of cement production industries, due to its high demand for energy and resources, and because of the calcination of limestone and fuel combustion in the clinker kiln (Kjellsen, et al., 2005). To produce 1 ton of clinker 3000-6000 MJ of thermal energy and about 1.6 tons of raw materials are needed (Van den Heede and De Belie, 2012). In the past, most fuels used in clinker kiln were coal and other fossil fuels such as diesel oil. Due to the environmental concerns, the impacts of fuel combustions on the environment and increasing fuel costs lead to using alternative fuels and also substitution of wastes for primary resources (Cementa AB, 2012).

Anläggningscement or CEM I has so many applications in different constructions such as bridges, due to its durability which is associated with its high clinker content. In order to identify all the possible areas for improvement and control the environmental impacts of CEM I through its entire life cycle, a life cycle assessment (LCA) model has been developed from cradle to gate as a method of analysis. The LCA model can specify in which stages of a product's life cycle, main environmental impacts occur and it can be used as a reliable assessment tool.

There have been few LCA studies done on comparing the environmental performance of different bridges made of different construction materials. The significance of accomplishment of these studies is to allow constructors to make a decision and design in order to obtain more environmentally benign bridges.

In this project, a life cycle assessment (LCA) model of a concrete bridge that has been built in the north part of Stockholm is carried out in order to identify total CO_2 emissions and energy consumption during the entire life cycle of the bridge, from cradle to grave. CO_2 uptake

(carbonation) as an inherent feature of concrete is calculated during both use phase of the bridge and its different end of life treatment scenarios.
Moreover, the environmental performance of the studied concrete bridge is compared with an existing wooden bridge based on total CO_2 emissions and energy consumption.
In the study, the Finnish LCA software KCL-ECO was used as a basis. KCL-ECO is developed and maintained by KCL- the Finnish Pulp and Paper research institute and in this project it was refined to suit CEM I production, concrete production and concrete bridge production.

2-Goal and objectives

This study aims to:

- Present accurate data on inputs, emissions and energy consumption related to manufacturing of one ton of Portland cement, CEM I, which is produced in Degerhamn, and develop a streamlined life cycle assessment (LCA) model of one ton of Portland cement from cradle to gate in the LCA software KCL-ECO to calculate total CO_2 emissions and energy consumption. The results are to be used by Cementa AB within HeidelbergCement.
- Develop a life cycle assessment model of a concrete bridge from cradle to grave in KCL-ECO. The life cycle inventory (LCI) of the Portland cement is the basis of the LCI of the concrete and concrete bridge. These LCIs are used to develop the life cycle assessment (LCA) model of the concrete bridge.
- Propose different scenarios for waste handling of the concrete bridge after its service life.
- Provide a reliable calculation method for CO_2 uptake (carbonation) during the life cycle of the concrete bridge.
- Compare environmental impacts of a bridge made of wood with the concrete bridge during their whole life cycle and show which construction material has better environmental performance on the bases of CO_2 emission and energy consumption.
- Design a virtual concrete bridge with the same size and shape as wooden bridge and compare it with the wooden bridge in order to show how different assumptions may affect the results of comparison.

3- General methodology

Life cycle of the different materials and services may contain different stages such as extraction of raw materials, preparation of raw materials, production phase, use phase, end of life treatments and transportation.

In order to evaluate a product or material from an environmental point of view, it is important to consider the entire life cycle of the product to make sure that environmental burdens from all stages of the product's life cycle are considered. Therefore, a logical and well-structured methodology and analysis methods as well as computer modelling and calculation are required to meet this goal. Life Cycle Assessment (LCA) is one of the most efficient and common methods that can be used to control the environmental impacts of a product during its whole life cycle.

In this chapter concepts of the LCA are described according to the International Organization for Standardization (ISO).

3.1- Life Cycle Assessment (LCA)

According to ISO 14040 (ISO, 2006), since environmental impacts which are related to produced and also consumed product, are of the most importance, developing a method that can make these impacts more understandable has drawn attention. One of the techniques that has been developed for this goal is life cycle assessment (LCA).

Some of the purposes of the LCA that can be mentioned here are:

- Specifying the possibilities to improve the environmental performance of a product during its life time;
- Helping decision makers to make more informed decisions;

- Selecting appropriate environmental performance indicators, including measurement techniques;
- And marketing.

In other words, LCA is a technique to assess environmental impacts of a product during its entire life from cradle to grave (e.g. from raw material extraction, materials preparation, manufacturing, distribution, use, end of life treatment, recycling and disposal).
LCA studies may include goal and scope definition, life cycle inventory, impact assessment and interpreting the results.

3.1.1- Goal and scope definition

Goal of the LCA should be stated based on the desired application and the main reason for performing the LCA. It's better to mention for whom the results are aimed.
Generally the scope of the study includes system boundary, functional unit and assumptions.
Functional unit determines what is being studied and all inputs and outputs in the LCI are related to the functional unit. The functional unit defines the quantified performance of a product system to provide a reference to which the inputs and outputs are related.
The system boundary shows all the stages of the life cycle that are included in the environmental assessment.

3.1.2- Life Cycle Inventory (LCI)

Life cycle inventory indicates all the inputs and outputs to the system needed to produce the specific functional unit according to the defined goals.

3.1.3 Life Cycle Impact Assessment LCIA

Life cycle impact assessment (LCIA) is the third phase of the LCA. It helps assessing the LCI to show environmental performance of the product better.

3.1.4- Interpretation

The last phase of the LCA is interpreting the results, in which the results of the LCI or LCIA, or both are summarised and interpreted as a basis for conclusions or recommendations for decision makers to make more informed decisions.

4- System model

In this chapter LCA research which is specific to this study has been discussed. Life cycle assessment of the product has been divided in three LCAs forms “cradle to gate”, “cradle to use phase”, and “cradle to grave”. The application of the use phase that has been chosen for CEM I is a bridge.

4.1-Cradle to gate model of Portland cement

Portland cement is a fine, grey powder that consists of a mixture of hydraulic cementitious materials comprising primarily hydraulic calcium silicates, to which calcium sulphate is added. Hydraulic cement hardens by reacting chemically with water.

A streamlined LCA of specific Portland cement has been performed from cradle to gate; the model has been developed in the LCA software KCL-ECO. Environmental indicators that have been calculated are carbon dioxide and energy consumption. In order to calculate these indicators for production of Portland cement, it is needed to consider everything from extraction of raw materials, preparation of raw materials through production phase and also transportation should be considered.

Anläggningscement or CEM I 42.5 N-SR3 MH/LA, is a Portland cement which is produced in Degerhamn plant in Öland, Sweden and is suitable for being used in bridges and heavy concrete foundations. It is also suitable to be used in conditions that are heavily exposed to the environment e.g. frost, sea water and salt used to melt snow. This Portland cement is used in applications demanding moderate heat development, sulphate resistant, and low risk of alkali silica reactions (Cementa AB, 2012).

The model in KCL-ECO is shown in Appendix A, Figure 1 to understand the study and different analyses better. The model consists of different processes and transportation flows for manufacturing of Portland cement. It starts with raw material and fuel processes needed for clinker production in the kiln.

The next step is grinding of clinker with different input materials to produce cement. Cement production processes can be found in section 4.1.2. Cement is then used to produce concrete.

4.1.1-Product application

Portland cement is one of the most widely used construction materials on earth. It is used to make bridges, dams, sidewalks, buildings, roads, etc. Concrete is composed of paste and aggregate. Cement reacts chemically with water to form paste. If paste is added to aggregates (mainly sand and gravel), it binds the aggregates together and forms concrete.

4.1.2-Cement manufacturing process

One of the first cement plants in Sweden was built on the Baltic Sea Island of Öland, where production began at Öland's Cement Ltd. in 1888. Today, the Degerhamn plant focuses on manufacturing a special type of cement for heavy concrete constructions that has a low heat development. This cement is particularly suited for use in bridges and heavy concrete foundations that are exposed to severe stresses from the environment. Approximately annually 300,000 ton of CEM I is produced in the Degerhamn plant. Figure 1 indicates different stages, material and fuels needed to produce CEM I.

1- Mining and crushing limestone; cement is made mainly from limestone. Limestone is quarried and brought to the cement plant. Limestone contains mostly calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$). It is crushed to a maximum size of 80 mm.
2- Preparation of raw meal; 85% of crushed limestone is ground together with other materials such as Alox (Alox is waste from aluminium industry), Bauxite, LD dust (by-product) and sand. The mixture is called raw meal. In order to have a reaction at lower temperature, some iron or aluminium oxides are added to prepare the melting phase in the kiln.

3- Cyclone tower with pre-calcination; it acts as a preheater that helps to decrease the demand for energy in the clinker kiln.

4- Clinker kiln; raw meal is fed into a rotating kiln. Maximum temperature in the kiln is around 1450 ^{o}C. Here calcium carbonate ($CaCO_3$) is split into calcium oxide (CaO) and carbon dioxide (CO_2). The chemical reaction is: $CaCO_3 + \text{heat} \longrightarrow CaO + CO_2$ and the same reaction happens for magnesium carbonate ($MgCO_3$). Chemical reaction is MgCO3 + heat $\longrightarrow$ MgO+ CO_2. Most of the energy in cement production is used in the calcination process. Fuels used in the kiln are hard coal, diesel oil, converted fuel oil, solvent waste, and plastic pellets. Coal is used more than other fuels. Finally clinker is produced in this stage.

5- Clinker cooler; here clinker is air cooled.

6- Clinker silos; finished clinkers are stored here.

7- Adding Gypsum and other additives; additives help to improve the quality of the cement. The proportion of the materials is 95 % clinker, 4 % gypsum $CaSO_4$, and the rest is crushed limestone, Ferro sulphate, and grinding aid products.

8- Cement mills; gypsum and other materials are ground together with clinker to produce finished cement.

9- Cement silos; the finished cement is loaded and stored here to transport to concrete plant.

Degerhamn plant is one of the oldest plants, for that reason, just one of the kilns in this plant is equipped by cyclone tower. Therefore, there is an intensive energy demand to increase the temperature in the kilns, which in turn causes a large amount of CO_2 emissions by combustion of the fuels in the kilns.

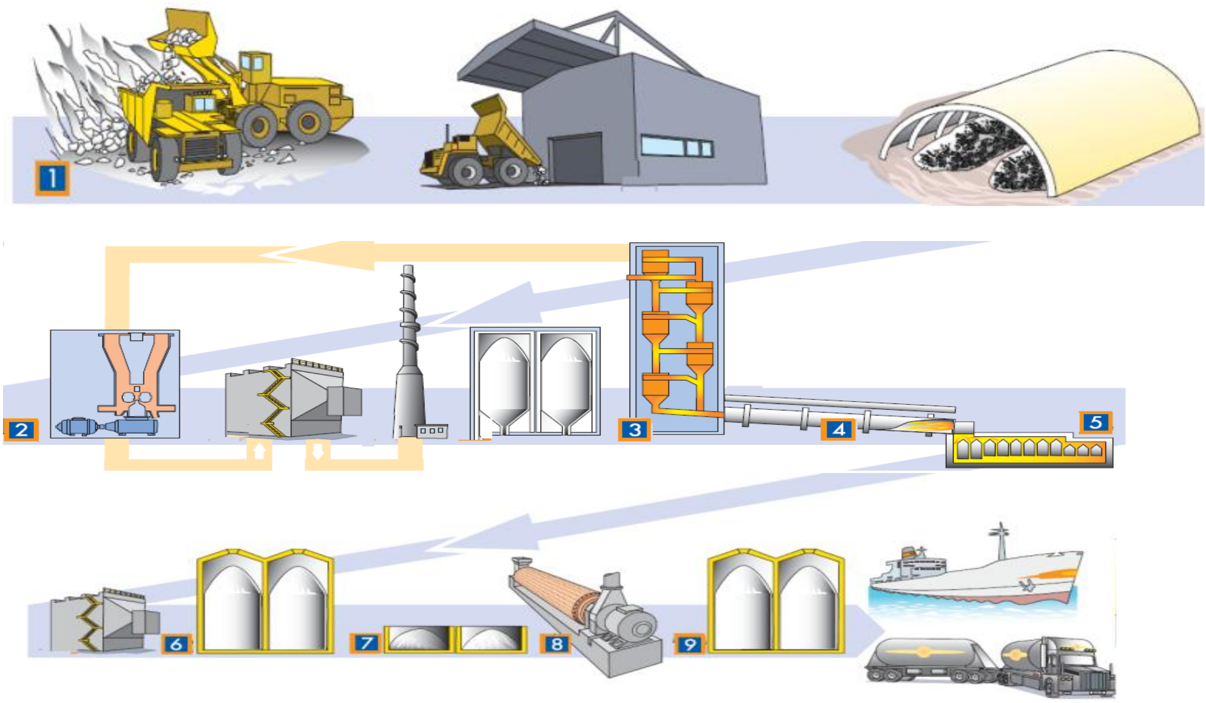


Figure 1. A simplified chart of Portland cement production (Cementa AB, 2012)

4.1.3-Declared unit

The declared unit is defined as 1000 kg of CEM I manufactured in Degerhamn plant. The LCI data in this report are presented in terms of a unit mass of cement.

4.1.4-System boundary

All steps defined in Figure 1 are included in the system boundary. System boundary also includes transportation of all materials and fuels from their source to the cement plant. Furthermore, emissions from combustion of the transportation fuels in the engines are included in the scope of the selected environmental impact assessment. Some of the raw materials are as by-products and their environmental impacts are excluded from the scope of the LCA.

The ISO 14041 guidelines (ISO, 1998) suggest that ''energy and material flows that do not constitute a significant portion of intermediate or final products need not be included in the LCI if they have a negligible environmental impact.''

Furthermore, environmental burdens of materials and energy needed for manufacturing of the infrastructure of the cement plant and operation of the plant are not included in this LCA.

4.1.5-Calculation methodology

This study has focused on identifying carbon dioxide (CO_2) emissions to the atmosphere and energy consumption for manufacturing 1000 kg of CEM I. In order to control emissions to air and energy consumptions and determine which sources or parameters have the most impact on these environmental indicators, it is needed to use an analysis method such as LCA methodology.

According to the aim of the study and data availability, system boundaries and data are selected. Therefore results will be affected by precision of the data input. In this study the sources of raw materials, energy and CO_2 emissions were judged as reliable since they were taken from the actual production in the Degerhamn plant.

4.1.6-Information source

Cementa AB has its own production data at Degerhamn plant which was collected in 2011. Moreover, there is some primary information that was collected from different literature sources as well as taken from an existing LCA report (Stripple, 2011).

This master thesis report contains complete information about raw materials, fuels, water, electricity and transportation modes used to produce Portland cement. Then secondary data is calculated in KCL-ECO software.

KCL-ECO. KCL-ECO is a type of LCA (life cycle assessment) software which has been developed and maintained by KCL- the Finish Pulp and Paper Research Institute.

The KCL-ECO software consists of mainly the following two components:

- KCL-ECO LCA calculation program: a program designed for carrying out intensive LCI and LCIA calculations.
- KCL Data Master: a program for creating and maintaining large LCI- databases (databases containing LCA modules (unit process) data).

Fuel and electricity. Data on fuel consumption and heating value are primarily from the manufacturing plant. Heating value has been used to convert units of fuels such as mass or volume to units of energy.

Types of electric power used are electric power system-Swedish average (Stripple, 2011) and electric power system-OECD production. Information about OECD is gained from IEA (International Energy Agency) statistics.

Transportation. Information on transportation modes are supplied by the manufacturing plant and distances from each source to Degerhamn plant is measured by Google Earth software and verified with online sources.

Transport data per ton-km for different transport modes has been obtained from NTM (2012). There is detailed information on emissions to the air from fuel combustion in the engine from modes of transportation in Appendix B Table 1.

Emissions. Data on emissions comes from a variety of sources. Some of them are taken from the company (Cementa AB) and some from an existing LCA report (Stripple, 2011), and then recalculated in KCL-ECO software per 1000 kg of Portland cement.

4.1.7-Results of cradle to gate model of Portland cement, allocation of emissions, energy and fuel to each process step

The total electricity demand for manufacturing of 1000 kg of cement is 397 MJ. Of this, 37 % is consumed in the cement mill process, 29 % in the clinker production process, 29 % in the raw meal preparation to produce clinker and the rest for manufacturing of other raw materials. Examples of the latter are coal production from mine, bauxite production, mining and crushing limestone, etc.

The total heat of combustion in the kiln is about 4270 MJ per ton of cement. The proportion of the fuels in the kiln is shown in Table 1.

Table 1. Percentage distribution and amounts of fuels consumed in the kiln per ton of cement

Type of Fuels	Amounts (MJ)	Percentage (%)
Hard coal	3351	78.5
Gasoline	6	0.1
Converted fuel oil	440	10.3
Plastics	302	7.1
Solvent wastes	171	4
Total	**4270**	**100**

Production of clinker is energy demanding because a high temperature is needed in the kiln. According to Table 1, heat of combustion is gained more from non-renewable resources or fossil fuels. Since global warming mitigation and natural resource conservation are crucial issues to be considered, cement industries are looking for alternative fuels such as solvent waste, plastic pellets, fly ash fuel, meat and bone meal. These fuels are gained from waste or residue products. In addition to reduction of emissions to the atmosphere, fossil fuels consumption can be reduced by increasing use of biomass fuels.

Clinker production causes the largest CO_2 emissions due to the calcination process and fuel combustion in the kiln.

Total fossil CO_2 emissions to the atmosphere from manufacturing of 1000 kg CEM I is 834 kg, of which 438 kg and 382 kg are related to calcination of limestone and fuel combustion respectively and the rest is related to other processes, such as transportation, electric power production, etc. (see Table 2).

Table 2 shows the main processes which contribute to fossil CO_2 emissions. In addition, Table 3 shows total biogenic CO_2 released from production of 1000 kg cement.

Table 2. Amounts and sources of fossil CO_2 emissions from production of 1 ton of cement

Processes	Amount of CO_2 (kg)	Proportion (%)
Combusted fuels in the kiln	382	45.8
Calcination of limestone	438	52.5
Electric power	3	0.4
Transportation	5	0.6
Operation of diesel driven vehicles	4	0.5
Production of gasoil	1	0.1
Others	1	0.1
Total	**834**	**100**

Table 3. Amounts and sources of biogenic CO_2 emissions from production of 1 ton of cement

Processes	Amount of CO_2 (kg)	Proportion (%)
Converted fuel oil	1.1	7
Plastic pellets	12.3	77
Solvent waste	0.6	4
Electric power	2	12
Total	**16.0**	**100**

Other emissions contributed by producing 1000 kg Portland cement are shown in Appendix B Table 2.

4.2-Cradle to use phase model of the concrete bridge

Today materials with less environmental burdens are needed in order to reduce carbon dioxide, energy consumption and conserve natural resources. Concrete is a sustainable construction material with durable and low maintenance attributes. It is possible to make concrete which is durable for a hundred years, for instance it was reported in 1983 that the concrete had still high quality although it had been manufactured in 1847 (Idorn and Thaulow, 1983).

Another advantage of concrete is that raw materials needed to produce cement and concrete can be found all over the world so transportation doesn't affect the environment significantly. There are some alternative materials that can be used for cement and concrete production to make it more environmentally adapted. Prior to being environmentally friendly the quality of the concrete according to its application should be considered, since alternative materials may jeopardize the quality and consequently the durability of the concrete products.

Concrete is produced by mixing cement with fine aggregate (sand), crushed aggregate (crushed stones) and water. As it has been mentioned before, cement reacts chemically with water to produce paste and then paste is added to aggregate to form concrete. Concrete is the most widely used construction material.

In order to estimate environmental impacts of a construction material it is important to consider all stages in the life cycle of the material. Each product is made from a combination of different raw materials, consumption of energy and with some associated wastes.

4.2.1-Goal and scope of the study

This section aims to analyse concrete production and bridge manufacturing. In order to meet this goal, LCA has been used as the basis of analysis. The model has been developed in KCL-ECO. Moreover the objective is to identify total CO_2 emissions and energy consumption from manufacturing of one pedestrian bridge named Stjärntorget, located north of Stockholm, Solna.

It should be noted that its construction hasn't been completed yet at the time of writing this report.

It is also of importance to show where in the life cycle of the bridge major environmental impacts occur. In addition, the total amount of CO_2 which is absorbed during the use phase or concrete carbonation has been calculated and discussed in detail. The useful lifetime of the bridge has been assumed to be 80 years.

System boundaries of the LCA of the bridge include extraction of raw materials needed to produce cement which is discussed in detail in the previous section (see section 4.1.2) then different processes needed to build one bridge. The functional unit which is considered for this study is one pedestrian bridge (total volume of the bridge is 493 m^3 with inclusion of steel reinforcements in the volume of the product) with a total length of 19.8 m, a width of 9.9 m and a total span of 19.5 m.

A schematic picture of the bridge is shown in Figure 2.

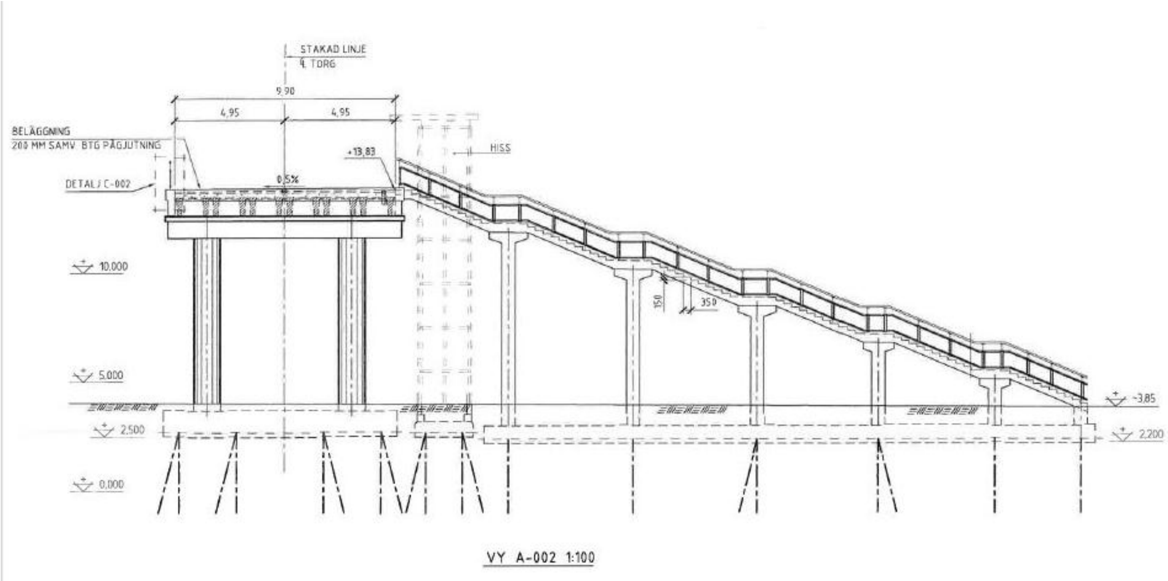


Figure 2. Schematic figure of the bridge from lateral side

4.2.2-Concrete bridge manufacturing

The model structure of cradle to use phase of the concrete bridge in KCL-ECO is shown in Appendix A, Figure 2. It contains different processes from extraction of raw materials trough concrete production and bridge manufacturing to the use phase.

After cement is produced in the cement mill, it is mainly used to produce construction materials. The cement is mixed with different materials based on different concrete products. In general concrete consists of a large amount of course and fine aggregates, a moderate amount of cement and water. All of these materials have their own production processes and environmental impacts. In order to show the environmental effects of concrete products, it is necessary to consider the impacts of each production process separately.

Production of CEM I has been discussed in detail in cradle to gate processes (see chapter 4.1).

The fine and course aggregates are usually mined separately. Aggregates can be obtained by recycling of the concrete too but in this case it is obtained by mining. Here crushed aggregates and sands in different fraction sizes are used. Some amounts of energy are required in all these processes.

Water in concrete is normally tap water with no processing. The amount of water used to produce concrete is shown in the model.

The model contains two different types of concrete production, on site cast production or ready mixed concrete and precast production. Some parts of the bridge are constructed from on-site cast concrete and some parts from precast concrete.

The type of cement used to produce on site cast concrete is CEM I (construction cement). Cement is mixed with other constituents in a ready-mixed concrete plant to produce concrete. The process has been indicated in KCL-ECO in the module “concrete production (on site casting)“.

Precast elements are made of CEM II (Building Cement). CEM II is a Portland cement which contains mainly 82.2 % clinker, 4.8 % gypsum, 12.5 % limestone and 0.5 % iron sulphate (Stripple, 2011). Explanation of the production process of CEM II is not included in this study but environmental impacts of its production process have been considered in the LCA of the bridge manufacturing. Concrete used in structural applications generally includes some amounts of steel reinforcements, and in some applications this steel is pre-stressed. Pre-stressed concrete is often precast. Precast elements in the bridge such as six cassettes and three beams under the bridge are manufactured in the factory and then transported to the construction site. Total volume of the product manufactured is 66 m^3. The module “Precast Production” in KCL-ECO represents precast elements manufacturing. For joining some parts of the bridge which is built in factory together in construction site, some small amounts of concrete are needed, which concrete is made of CEM II too and the production process has been indicated in the module “Concrete production (precast)” (See Appendix B, Figure 2).

The proportions of the components in the two types of concrete used in this study are presented in Table 4.

Table 4. Amount of raw materials consumption for production of 1 m^3 on-site cast and precast concrete

Concrete Bridge	CEM I (kg)	CEM II (kg)	Crushed aggregates (kg)	Pit run sand and gravel (kg)	Water (kg)	Concrete weight (kg)
Concrete production (on-site casting)	420	-	877	844	198	2339
Precast Production	-	350	1875	-	150	2375
Concrete Production (Precast)	-	375	854	890	183	2301

According to Table 4 the recipe of the concrete varies based on application demand and where it is used in the structure.

After the ready-mixed concrete has been produced in the ready mixed concrete plant, it is hauled to the construction site by truck to build some parts of the bridge. Parts of the bridge constructed on site casting are surface of the bridge, two rounded columns, the wall under the bridge, and foundations. Total volume of the product measured is 427 m^3. Module “Concrete Product Production (on site casting)” represents the construction process, amount of energy, steel reinforcements and concrete required to produce this volume of the product.

Precast production and small amount of concrete are transported to the construction site to be joined together. The module “Precast on site construction” shows the construction process.

4.2.3- CO_2 uptake in concrete bridge

During the use phase of the bridge, maintenance doesn't take place and there won't be any greenhouse gas emissions and energy consumption. The only process that should be considered is carbonation or CO_2 uptake by the concrete product and there is no need to cover the surface of the bridge with paints or other materials. The objective is to provide a reliable calculation method for CO_2 uptake (carbonation) in the concrete bridge during its service life. In this study the useful life time of the bridge is assumed to be 80 years. Then after 80 years, it will reach its end of life, which will be discussed in detail in section 4.3.

4.2.3.1-Mechanism of carbonation

Carbonation is a chemical process and it is the reverse reaction of calcination of the limestone in the kiln to produce clinker. CO_2 which is released from calcination will react with CaO in the concrete to form calcium carbonate (CaCO3) (Kjellsen, et al., 2005).

Carbonation starts from the surface of the product and progresses inwards, the diffusion rate of CO_2 affects the carbonation. Rate of carbonation at the surface of the concrete product is higher than the inner part, since the surface is in contact with water and CO_2. Based on the structure, the type of concrete and the environment that the concrete is exposed to carbonation will occur within years, decades or centuries. Despite the advantages of the carbonation, CO_2 uptake should be controlled because it can cause corrosion in steel reinforcements and will affect the concrete product strength. Therefore cement and concrete industries have thought of this phenomenon. The carbonation process will slow down at a specific depth in the concrete product; in this area there isn't any steel reinforcement that is exposed to the corrosion (Stripple, 2011).

Parameters that affect the carbonation depth are size and geometry of the concrete pores, amount of water saturated in the pores, concrete construction, the proportion of the cement in the concrete, and environmental conditions (Kjellsen, et al., 2005).

There is an approach to measure the depth of carbonation of concrete by covering it with a solution of phenolphthalein; it can be found out that the carbonated concrete will stay colourless, while the un-carbonated one will alter to pink colour.

The depth of carbonation can be measured according to the square root of time. It can be calculated by equation (1) (Kjellsen, et al., 2005):

$$d_c = K.(t)^{0.5} \tag{1}$$

where d_c is carbonation depth (mm); K is the carbonation rate factor ($mm/\sqrt{year}$); t is time (year).

The carbonation rate factor (K) will be affected by the surrounding environment of the concrete product and the quality of the concrete. According to Table 5 (c.f. Lagerblad, 2005), the carbonation rate factors for bridges vary with different compressive strength classes and depending whether some parts of the bridge are exposed to rain and some parts sheltered.

Table 5. Carbonation rate factor according to the concrete quality and exposure conditions

	Compressive strength=>35 MPa (CEM I)	CEM II	unit
	Carbonation rate factor (K)	Carbonation rate factor (k)	
Exposed	1	1.1	mm/√year
Sheltered	2.5	2.6	mm/√year

As Lagerblad (2005) showed ''approximately 75 % of the original CaO of the cement is carbonated at the pH of the phenolphthalein colour change''. Therefore it can be assumed that the degree of carbonation is 75 %. So the amount of CO_2 bound in a unit volume of the concrete can be calculated from the following equation (Nilsson, 2011):

$$a = C.\frac{CaO}{C}.\frac{(CaO)co3}{CaO}.\frac{Mco2}{Mcao} \tag{2}$$

Where a is the amount of CO_2 bound in a unit volume of the concrete (kg/m^3); C is cement content in the concrete (kg/m^3); CaO/C is the amount of CaO per weight of Portland cement; $(CaO)_{caco3}$/Cao is degree of carbonation; M is molecular weight.
Then CO_2 uptake of a unit area of concrete can be calculated as below, if it is assumed that ''a'' is constant throughout the carbonated layer (Nilsson, 2011):

$$m_{CO2} = d_c.a \tag{3}$$

Where m_{co2} is the amount of CO_2 uptake bound in a unit area of the concrete (kg/m^2).
Theoretically it can be expected that in an infinite time period, all the CO_2 released from calcination of limestone in the kiln can be absorbed by the concrete during the waste handling. Therefore the maximum potential amount of CO_2 uptake can be defined as total CO_2 emission from calcination of raw meal in the kiln.
Final results of carbonation calculations are presented in detail in section 4.2.5.

4.2.4-Results of the cradle to use phase model of the concrete bridge on materials used and energy consumption

Table 6 shows the total amount of materials needed to build the bridge.

Table 6. Amounts of materials required for manufacturing the concrete bridge

Raw materials		Units	Amounts	Sum
Cement	CEM I	ton	177	200
	CEM II		23	
Concrete weight	on-site cast concrete	ton	983	1146
	precast concrete		163	

Concrete volume	on-site cast concrete	m^3	420	487
	precast concrete		67	
Steel reinforcements	on-site cast concrete	ton	51	78
	precast concrete		1	

Of the total volume of the bridge, 86 % is made from on-site cast concrete. Therefore, the environmental impacts of manufacturing the bridge mostly originate from the on-site cast part.

Primary energy is an energy form found in nature that has not been subject to any conversion or transformation process. It is energy contained in raw fuels, and other forms of energy carriers received as inputs to a system. Primary energy can be non-renewable or renewable.

In other words, the primary energy resource used represents fuels consumed in the production process in order to generate heat or electricity; moreover it can represent as transportation fuel. Table 7 shows the total primary energy resources used for manufacturing the concrete bridge.

Table 7. Total primary energy resources used for manufacturing the concrete bridge

Primary energy resources	Amounts (GJ)
Coal	640
Crude oil	661
Natural gas	11
Nuclear energy	651
Biomass fuel	16
Hydropower	217
Wind power	1
Total	**2197**

Renewable primary energy resources used for manufacturing the concrete bridge consist of hydropower, biomass fuel and wind power; they are mainly used to generate electric power.

The following figures indicate the non-renewable primary energy resources used for manufacturing the concrete bridge. They show the proportion of each energy source in different processes. It can be seen which processes consume more energy.

(Note: In this report by mentioning clinker production means the amount of clinker needed to produce CEM I).

(Note: in Figure 3 to Figure 6, by mentioning ʺcementʺ and ʺconcreteʺ in the parentheses in the legends, means that the process with parentheses is related to either ʺCEM I productionʺ or ʺconcrete and concrete bridge manufacturingʺ.)

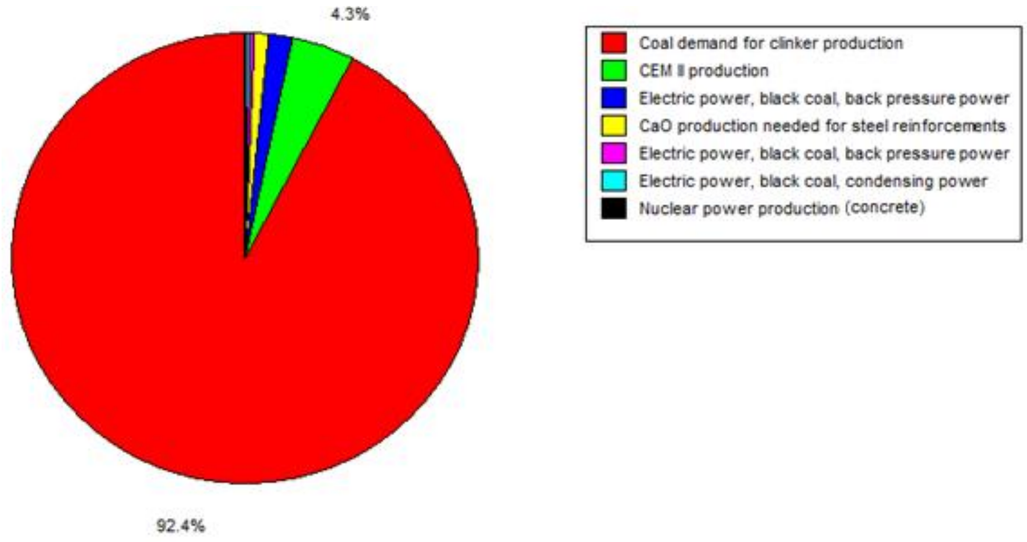


Figure 3. Coal as primary energy source for manufacturing the concrete bridge

The total coal consumption for manufacturing the bridge is 640 GJ. A significant amount of coal, about 92 %, is consumed in the clinker kiln, since the heat of combustion in the kiln is mostly from non-renewable resources. In addition about 4 % is consumed in CEM II production processes and the rest of it is used in electric power production. The electric power production mix contains some amount of coal as coal condensing power production, and nuclear power.

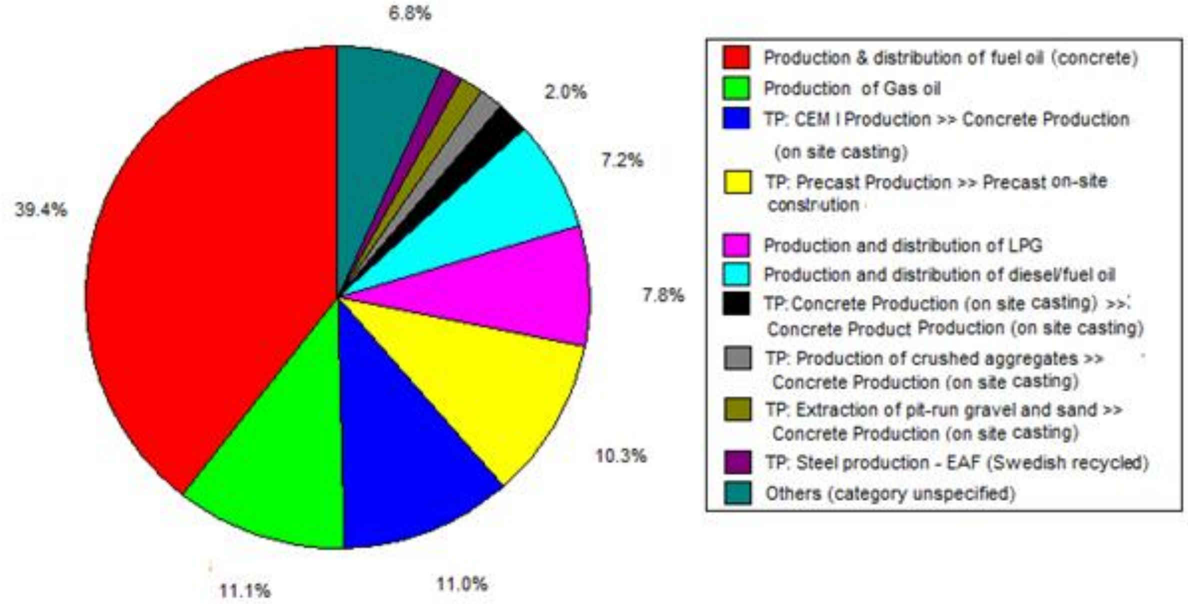


Figure 4. Crude oil as primary energy source for manufacturing the concrete bridge

Total crude oil consumed is 661 GJ. According to Figure 4, crude oil is mainly used to produce concrete; it is mostly related to use in construction vehicles and machines- about 40 %, fuels needed in concrete production process- 7 %, and fuel needed for steel reinforcement production 8 %. Meanwhile, a considerable amount of crude oil is used for transports as fuel combustion in the engines, about 27 %. About 11 % of the crude oil is needed for production of gas oil used for heating up the clinker kiln. The rest of it is consumed in other processes.

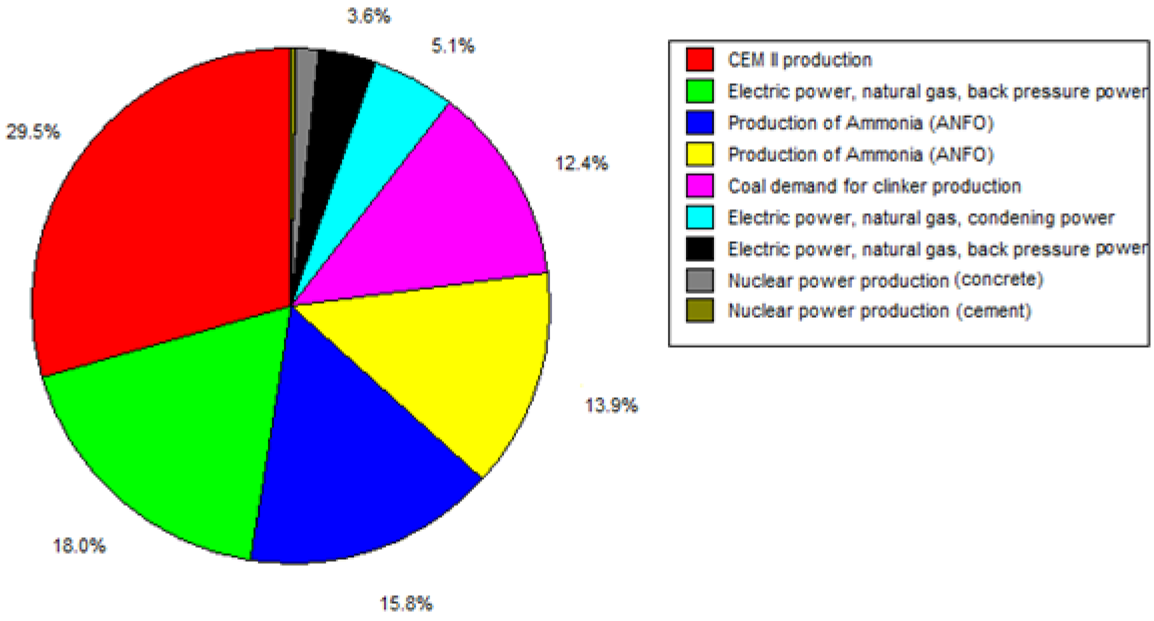


Figure 5. Natural gas as primary energy source for manufacturing the concrete bridge

Total natural gas used is 11 GJ. The amount of natural gas use is small in proportion to coal and crude oil. The use of natural gas is mostly related to the cement production processes. Some amounts of natural gas are used in coal production needed to heat the kiln. Natural gas is consumed to produce ammonia needed for production of explosives that are required for both mining of limestone and crushing aggregates.

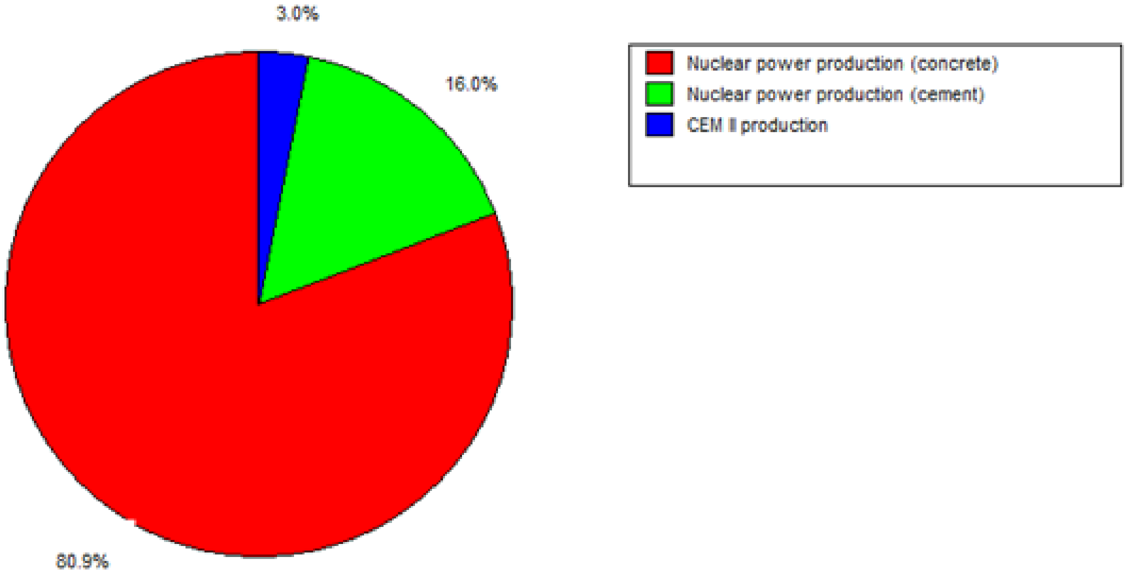


Figure 6. Nuclear energy as primary energy source for manufacturing the concrete bridge

Total nuclear energy used in the production process of the bridge is 651 GJ.

Electric power is mainly supplied by hydropower and nuclear power, since Swedish electric power production mix is predominantly used.
To produce the concrete bridge, the total amount of electricity used is about 420 GJ.
Table 8 shows the electric power consumption for the main processes, their amounts and proportions.

Table 8. Allocation of electric power to different process steps

Processes	Amounts (GJ)	Percentage (%)
Concrete product production (on-site casting)	188	45
Concrete production (on-site casting)	21	5
Steel production-EAF (Swedish recycled)	115	27
CEM I production	26	6
Raw meal to produce clinker	20	5
Clinker production	20	5
Production of crushed aggregates	10	2
Precast production	15	4
Others	5	1
Total	**420**	**100**

The total heat of combustion in the kiln to produce clinker is about 754 GJ. The proportions of the fuels, waste fuels and fossil fuels, in the kiln are shown in Table 9.

Table 9. Percentage and amounts of fuels combusted in the kiln to produce clinker required for manufacturing the concrete bridge

Type of Fuels	Amounts (GJ)	Percentage (%)
Hard coal	592	78.5
Gasoline	1	0.1
Converted fuel oil	78	10.3
Plastic pellets	53	7.1
Solvent wastes	30	4
Total	**754**	**100**

4.2.5-Results of carbonation calculation for the use phase of the concrete bridge and total CO_2 emissions from cradle to use phase

Table 10 shows the amount of carbon dioxide absorbed into the surface area of the bridge after 80 years:

Table 10. Results of calculations for different parts of the bridge

	Amount of CO_2 bound in a unit area of the concrete after 80 years	Unit
Parts of the bridge exposed to rain	2.4	kg/m^2
Parts of the bridge sheltered from rain	5.9	kg/m^2

Table 10 indicates that the amount of carbon dioxide absorbed per unit surface area of the bridge after 80 years is small, since the concrete construction is compact, due to the fact that the bridge is mainly made from CEM I with a high content of Portland cement clinker.

Detailed calculations and assumptions are shown in Appendix C, the depth of carbonation and amount of CO_2 uptake per unit area of the concrete is presented after different exposure times. As shown in the appendix, the amount of CO_2 uptake per unit area of the concrete is increasing considerably during the first 20 years and after that CO_2 uptake slows down.

In order to calculate the total CO_2 uptake after 80 years, the surface areas of the bridge which are exposed to or sheltered from rain should be measured and multiplied by the results in Table 10.

Figure 7 shows total CO_2 emissions and uptake for the concrete bridge from cradle to use phase.

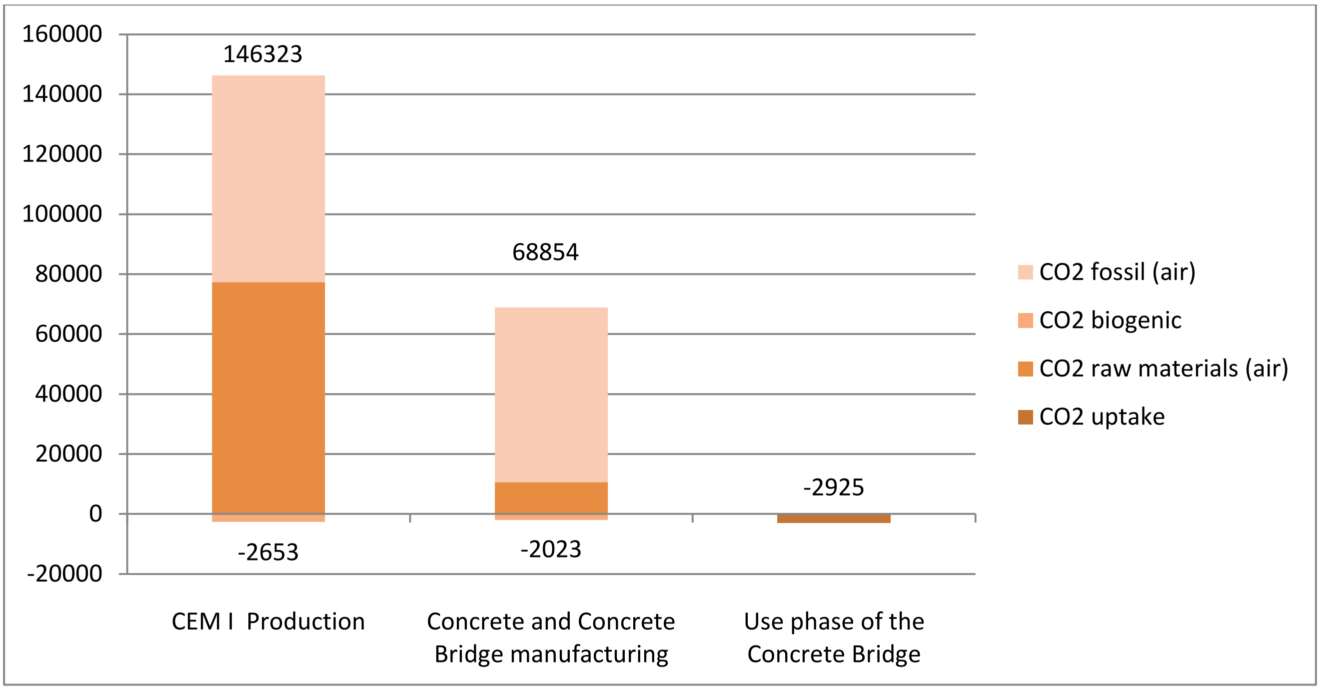


Figure 7. Total CO_2 emissions (kg) and uptake (kg) from ''cradle to use phase'' of the concrete bridge, shown divided into different process steps. The biogenic CO_2 emissions are contributed by biomass and waste fuels therefore they are considered as zero emissions, their amounts are shown in the figure as additional information.

The environmental impact of bridge manufacturing comes from different sources, but the highest amount originates from production of cement. Figure 7 shows total amounts of CO_2 emitted from manufacturing the bridge and total amounts of CO_2 uptake during the use phase. CO_2 emissions are divided into three groups. CO_2 emission from raw materials represents total amount of CO_2 released from calcination of limestone in the kiln to produce clinker. As it is clear, CO_2 biogenic is biogenic-based CO_2 emissions from biomass fuels and waste fuels. CO_2 fossil is total fossil based CO_2 emissions that originate mostly from combustion of fossil fuels in the kiln. Total fossil CO_2 emissions to the atmosphere are 127302 kg (146323 – 77287 + 68854 - 10588), of which more than half originates from fuel combustion in the clinker kiln to produce CEM I, 23 % from concrete production and bridge construction, 10 % from transports, and some small amount from electric power generation.

The total CO_2 uptake after 80 years is calculated 2925 kg. The total carbonation after 80 years is not high compared to total CO_2 emissions from raw materials in the kiln.

The total CO_2 emissions measured are 212252 kg (Total CO_2 emissions from CEM I production + Total CO_2 emissions from concrete and concrete bridge manufacturing – concrete carbonation in use phase).

Some other main emissions to the air from manufacturing the Bridge are shown in Appendix B, Table 3.

4.3-Cradle to grave model of the concrete bridge

Selection of different scenarios for waste handling or end of life treatment of the concrete products can affect CO_2 uptake significantly and consequently the total CO_2 emissions from the system. Also it can change the amount of energy consumed considerably. CO_2 uptake or carbonation of the concrete during the use phase is small, owing to the construction of the concrete bridge, therefore a large CO_2 uptake potential remains for the end of life treatment. The objective of this part is to present effective ways for waste handling of the concrete.

Currently some common waste handling systems for concrete products in Sweden are as follows (personal communication, Stripple, 2012):

1. Demolition of the concrete product into concrete pieces (including steel reinforcements)
2. Storage of demolished concrete for a time period of 0.5-4 years
3. Crushing of demolished concrete into smaller sizes. Steel is removed for recycling.
4. Use of crushed concrete in various applications such as landfilling, road construction or building construction. The crushed concrete is usually covered with some materials that cause less exposure to CO_2 in the atmosphere. These materials can last for 100-200 years in the constructions.

According to the literature and via personal communication, the CO_2 uptake resulting from current waste handling in Sweden is small in a 100 years perspective. Therefore some alternative methods for end of life treatments of the concrete should be developed in order to increase the CO_2 uptake.

Although there are always uncertainties for concrete carbonation both today and in the future waste handling systems, combining efficient treatment with lower energy use and higher CO_2 uptake, has always been the aim for concrete industries.

Two scenarios for waste treatment have been proposed and studied here. After the use phase, the bridge will be demolished into transportable pieces then two different methods will be applied to the demolished concrete:

1- Crushing and sieving of demolished concrete for increasing CO_2 uptake and using the crushed concrete in roads or as aggregates in new concrete. Also steel reinforcements are removed for recycling.

2- Landfilling of demolished concrete without recycling of concrete and steels.

4.3.1-Scenario 1

1-Crushing and sieving of demolished concrete for increased CO_2 uptake and using the crushed concrete in roads or as aggregates in new concrete. Also steel reinforcements are removed for recycling.

Crushing of the demolished concrete will increase the exposed surface area and increase the speed of diffusion of CO_2 into the concrete which in turn increases carbonation. Absorption of CO_2 needs air flow. It must be considered that sometimes small size particles prevent air circulation in the concrete. Sieving the crushed concrete into a desired size will make the circulation of the air easier. Afterwards the waste concrete is stored for 2 years to absorb CO_2. It is anticipated that up to 20 % of total CO_2 emissions from raw materials will be absorbed by the crushed concrete. But it should be taken into consideration that crushing of the concrete requires some amount of energy, about 21 MJ per ton of crushed concrete. After two years of storage the waste crushed concrete can be used in the system as crushed aggregates. 15 % of natural aggregates can be replaced by crushed concrete without causing any problem for the quality of the product (Stripple, 2011). In this study it is assumed that crushed concrete after storing and absorbing CO_2 is used as crushed aggregate and it won't take up any more CO_2. This replacement can affect energy consumption and total CO_2 balance.

After crushing of concrete, steel reinforcements are recycled and reused as scrap. This can have an effect on energy resource use and CO_2. The effect on CO_2 emission of using recycled steel is expected to be small since steel reinforcement used in this bridge is produced by using electric power generated in Swedish electric power mix and this power mix consists of mainly hydropower and nuclear that have low CO_2 emissions. Recycling of the steel reinforcement will lead to saving the iron resources too. In this study, it is assumed that 20 % of the steel reinforcement used is replaced by recycled steel. Using crushed concrete as crushed aggregates and using recycled steel in the system can compensate the amount of energy needed for crushing and sieving the concrete.

All changes caused by this waste handling system are discussed in the next section and the results are presented step by step.

4.3.1.1-Result of first scenario of waste handling system

24310 MJ Swedish electric power production mix is applied to crush the demolished concrete, thereby increasing the use of nuclear power and hydropower in the bridge life cycle by 6 %.

The energy needed for crushing of the concrete can be compensated for by steel recycling. Replacing 20 % of the steel required with recycled steel causes about 20 % decrease in total amount of electricity needed, which is almost equal to the amount of energy needed for crushing. Recycling of steel decreases the total amount of fossil CO_2 emissions to air insignificantly as it has been expected.

Storage of crushed concrete for 2 years results in an increase of CO_2 uptake from 2925 kg to 11711 kg. Meanwhile, using crushed concrete as aggregate decreases energy needed for production of crushed aggregates marginally. In order to store crushed concrete, 10.30 MJ diesel oil needed per cubic meter of concrete that results in a small amount of fossil CO_2 emitted to air. Final results from the first waste handling scenario are represented in Figure 8.

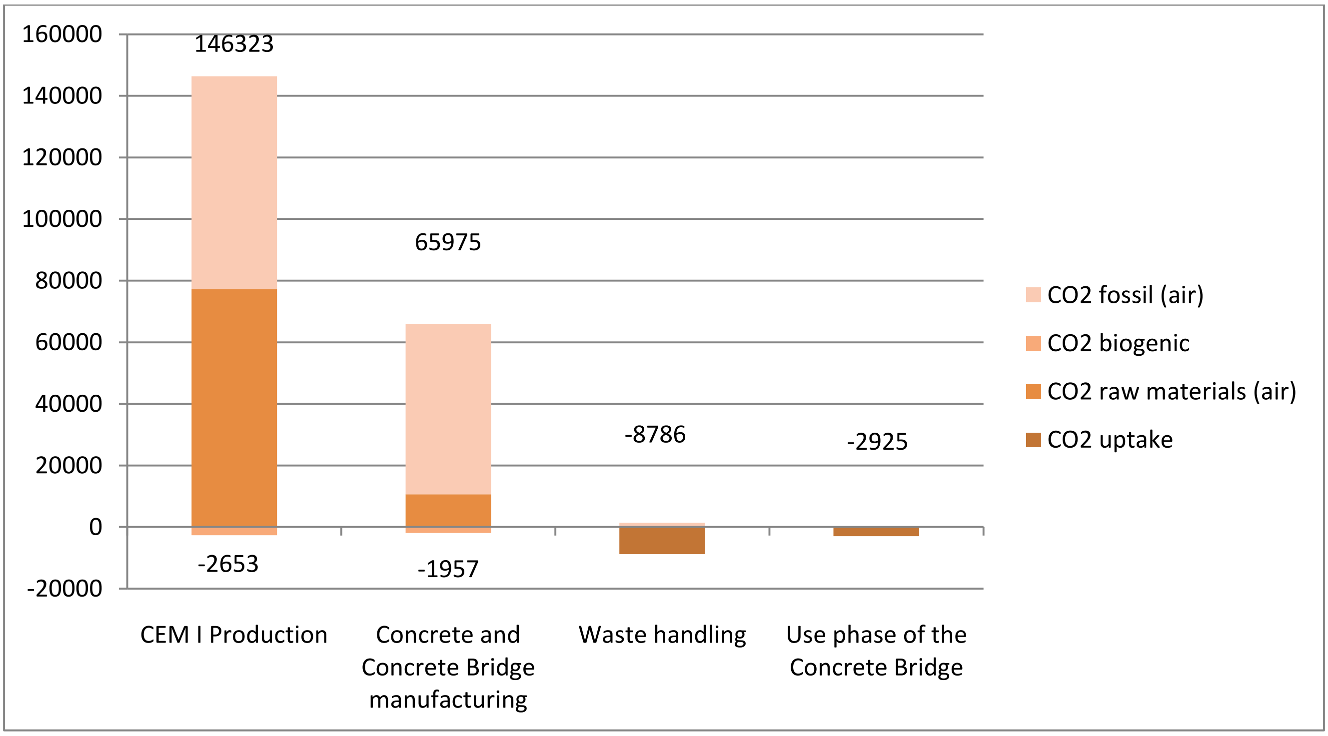


Figure 8. Total CO_2 emissions (kg) and uptake (kg) for the concrete bridge from ''cradle to grave'' related to the first scenario of waste handling, shown divided into different process steps. The biogenic CO_2 emissions are contributed from

biomass and waste fuels therefore they are considered as zero emissions, their amounts are shown in the figure as additional information.

The results support the idea that the main CO_2 emissions originate from cement production processes. According to the calculations in KCL-ECO, by applying first scenario, fossil based CO2 emissions decrease from 127302 kg to 124423 kg (146323 – 77287 + 65975 - 10588); that reduction is not considerable. Whereas, regarding the total CO2 uptake, CO2 emission released by calcination of limestone in the kiln decreases from 84950 kg (77287 + 10588 - 2925) to 76164 kg (77287 + 10588 – 2925 - 8786), corresponding to 10 % reduction.

Total CO_2 emissions measured is 200587 kg (Total CO_2 emissions from CEM I production + Total CO_2 emissions from concrete and concrete bridge manufacturing – CO_2 uptake during use phase – CO_2 uptake during waste handling).

The more the amount of biogenic CO_2 emission increases, the better environmental results gained, because of its zero impacts on the environment. It shows that renewable resources are substituted for non-renewable ones. But here there is no change in total biogenic CO_2 emissions.

Applying this scenario represents no change in the final amount of energy use.

4.3.2- Scenario 2

2-Landfilling of demolished concrete without steel recycling

Today landfilling of the demolished concrete without crushing and removing steel reinforcements is not common as an end of life treatment of the concrete products, due to some significant reasons like: high landfill fees, no process for steel recycling, and no process for crushing of the concrete to use in roads or as crushed aggregates. CO_2 uptake occurs slowly because generally landfills are covered with soil and this action will decrease the carbonation of the concrete. The only advantage of this waste handling system is that no energy is used for crushing of concrete and the only required energy is for demolition of the concrete bridge.

In this study, landfilling storage time was assumed to be 100 years. As mentioned before, concrete can absorb CO_2 for an infinite period of time but the near future was in focus. After demolition of the bridge, the demolished concrete was assumed to be directly landfilled. Section 4.4.2.1 presents the results from landfilling of the concrete.

4.3.2.1- Result of second scenario of waste handling system

According to the results, the amount of energy use doesn't change. Figure 9 shows the results gained for total CO_2 emissions.

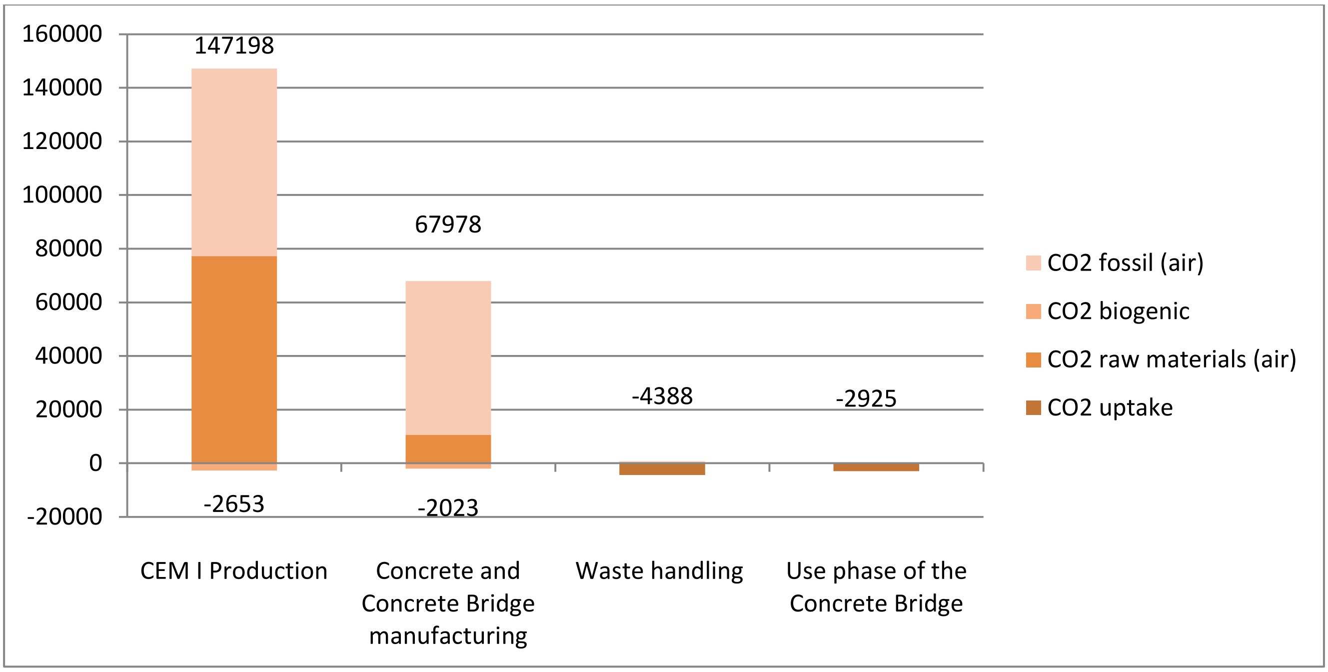


Figure 9. Total CO_2 emissions (kg) and uptake (kg) for the concrete bridge from ''cradle to grave'' related to the second scenario of waste handling, shown divided into different process steps. The biogenic CO_2 emissions are contributed from biomass and waste fuels therefore they are considered as zero emissions, their amounts are shown in the figure as additional information.

According to Figure 7 and Figure 9, regarding the total CO_2 uptakes, the CO_2 emissions from raw materials decrease from 84950 kg to 80562 kg (77287 + 10588 – 2925 - 4388), corresponding to 5 % reduction.

The total CO_2 emissions measured are 207863 kg (Total CO_2 emissions from CEM I production + Total CO_2 emissions from concrete and concrete bridge manufacturing – CO_2 uptake during use phase – CO_2 uptake during waste handling).

As is obvious, the first scenario has lower CO_2 emissions than the second one, although CO_2 uptake in concrete resulting from crushing and storing concrete was not considerable either.

The LCA model of the concrete bridge from cradle to grave in KCL-ECO is shown in Appendix B in Figure 3a and Figure 3b for scenario 1 and scenario 2 respectively.

5-Comparison of wooden bridge and concrete bridge

5.1-Previous research

Different LCA studies have been undertaken on environmental performance of bridges. It is obvious that, despite using a common approach (LCA), it is difficult to state which construction material is the best from an overall environmental point of view. This is since, such studies use different system boundaries and assumptions. Therefore it cannot be concluded with certainty which type of bridge has lower environmental burdens but such studies can be used as useful references.

For instance, in some cases wood-based industries consider carbon dioxide absorption in trees in the forest as an advantage of the wooden materials (Bouhaya, et al., 2008).

As shown by Bouhaya, et al. (2008), environmental impacts of a new bridge made of wood and high-ultra performance concrete has been evaluated during its entire life cycle and three scenarios considered for end of life treatments are: burying in landfills, incineration, and recycling. According to the results, considering CO_2 uptake in growing of trees, makes up CO_2 emissions from other stages of the bridge manufacturing. Therefore for the first two scenarios total CO_2 emissions are negative.

A comparison of different bridges constructed from different materials such as steel, wood, and concrete, shows that a concrete bridge has the best overall environmental performance over the entire life cycle, while a wooden bridge performs better according to the global warming perspective (Hammervord, et al., 2011).

5.2-Methodology

The choice of construction materials can have a huge impact on the environment and causes consumption of natural resources. Therefore considering the environment during construction can play an important role to reduce environmental impacts of the materials. In order to compare different building materials effectively, life cycle assessment is a useful method.

This chapter aims to compare climate and energy impacts of a bridge made of wood with the concrete bridge already evaluated in section 4.2, during their whole life cycles. The purpose of the life cycle assessment is to show how bridges might be improved in terms of climate and energy impacts.

A part of this purpose is to determine which steps in the life cycle of the bridges have the most important impacts and which constituents contribute to the climate and energy burdens.

In this study uncertainties exist, one of the important issues is that there are very few reference studies of wooden bridges, especially bridges with similar characteristics as the studied concrete bridge. Another important issue is that most bridges are different in size and configuration. In order to be able to compare the environmental performance of bridges, correction factors are needed that increase the depth of comparison. But finding all relevant correction factors for the bridges in this case study was considered out of scope of this thesis and exposed as future work.

As Hammervord, et al. (2011) present, in order to be able to compare different bridges made from different materials in different sizes (span, length, width) and in different locations, it can be assumed that first, LCA of each bridge should be calculated during its full life cycle individually and then total energy consumed and total emissions which are related to the entire life cycle of each bridge should be calculated per square meter of the bridge. Therefore the functional unit can be defined as ''1 square meter of bridge surface area'', since ''the surface area of the bridges is the effective area in use'' as Hammervord, et al. (2011) state.

Useful lifetimes of the bridges are not the same, the lifetime of the wooden bridge and concrete bridge is 40 years and 80 years respectively. Since the durability of a concrete bridge is twice that of a wooden bridge, another assumption introduced was that all emissions and energy consumption related to the wooden bridge should be multiplied by two.

5.3-LCA of the wooden bridge in the case study

The wooden bridge which is called Tidan Bridge was built over Tidan River in Vads Church in Skaraborg, Sweden in 1994. The LCA study of the Tidan Bridge was part of the Nordic project which was supported by Nordic Wood and Nutek. The bridge has a total width of 2.5 m, length of 46 m and a span of 45.5 m. The bridge surface area is 115 m^2 (Pousette, 1998).

A LCA of the wooden bridge was performed in connection to its construction and assuming a total service life of 40 years, manufacturing of the production equipment is not included in the LCA, necessary maintenance is included, and the LCA covers only wooden superstructure, the concrete foundations and columns are excluded.

The wooden superstructure consists of four longitudinal bars of laminated wood, short glued wooden pillars between the support and with transverse plank on top. The surface of the bridge is covered with a thin layer of asphalt.

5.3.1-Materials

The bridge consists of 50 % glue laminated wood, 23 % asphalt, 19 % impregnated wood, 6 % steel and the rest are paint, zinc, plywood, etc. Table 11 shows amounts of materials needed for manufacturing the wooden bridge.

Table 11. Amounts of materials needed in manufacturing process of wooden bridge

Material	Amounts (kg)
Asphalt	8763
Falun façade colour	196
Impregnated wood	7161
Glue laminated wood	19231
Plywood	15
steel	2315
Wood stain	185
Wood stain diluted	370
Zinc	89
other	143

5.3.2-Electric power

Production of electricity is included in the energy data, i.e. losses in distribution lines are included. Vattenfall's energy data for 1997 has been used for electricity generation.

5.3.3-Transportation

Transportation has been carried out by truck, boat and train.

5.3.4-Maintenance

Maintenance of the Tidan Bridge has been assumed to be performed every 10 years, 3 times in 40 years. Maintenance includes repainting of the surface, applying asphalt on the surface of the bridge, and under the bridge service life, replacement of up to 10 % of the wood railing is assumed.

5.3.5-End of life treatment of wooden bridge

The final phase of the bridge life cycle can be handled in different ways in a LCA study. It was assumed that the wooden bridge is demolished after 40 years and the materials recycled or energy recovered and the rests transferred to landfill. Table 12 presents a compilation of data for the bridge and assumed data for recycling, recovery and landfilling in future waste handling. It is assumed that carbon dioxide from combustion of biofuels is included in the forest cycle and does not contribute to global warming.

Table 12. Results of recycling and landfilling of materials of wooden bridge

Waste products, materials	Amounts (kg/m^2)	Materials recovery/ energy (%)	Landfill (%)	Effective energy value (MJ/m^2)
Wood (laminated wood, treated wood etc)	236	90	10	3754
Steel, Zinc	21	90	10	
Asphalt	76	80	20	
Others	1.2	0	100	

Figure 10 shows a conceptual model and all the stages in the life cycle of the wooden bridge which are included in the scope of life cycle assessment.

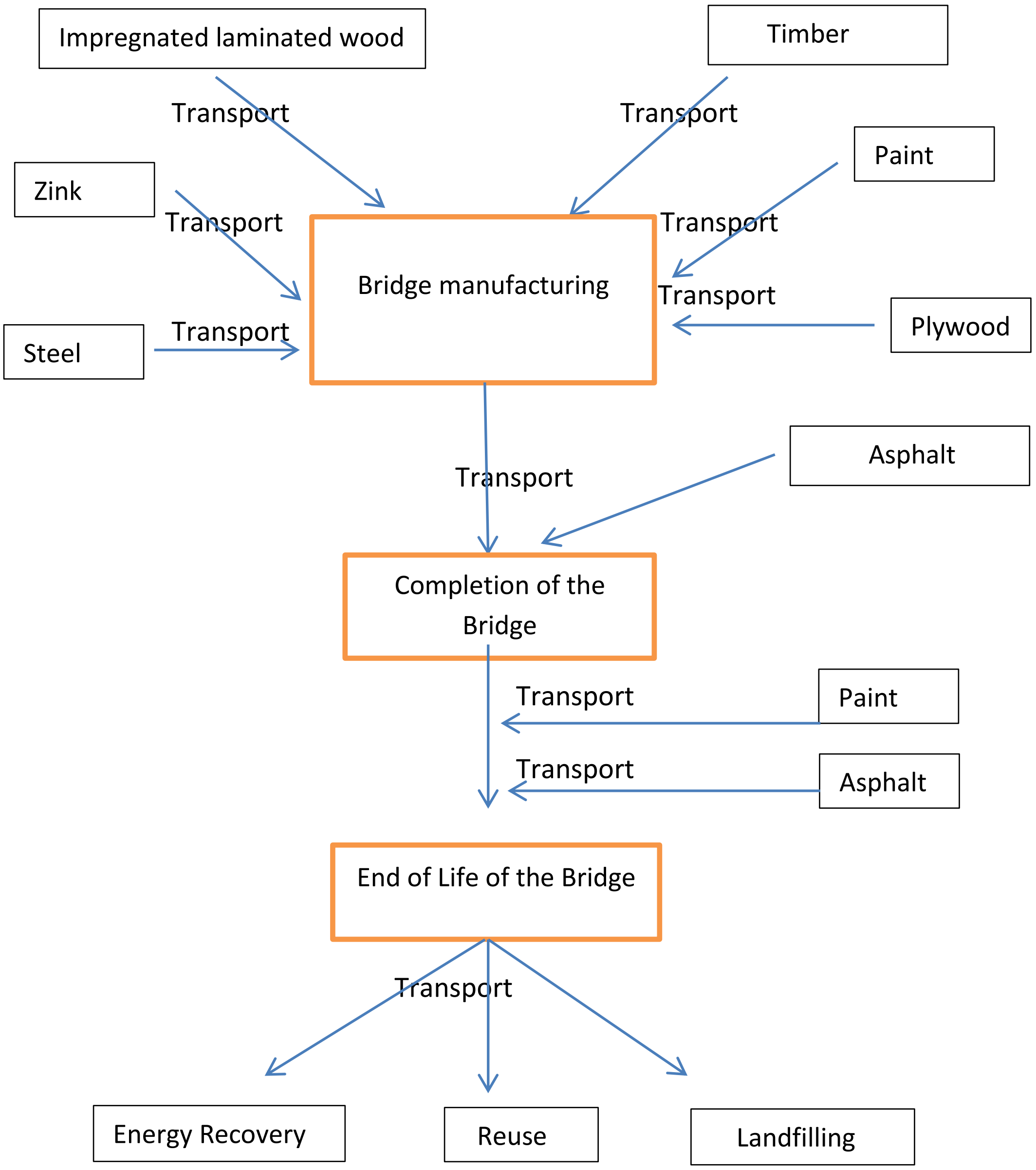


Figure 10. Conceptual model of the wooden bridge

5.4-Comparison of the results of the LCA of the bridges

5.4.1-Fuel consumption

A large part of the energy use in manufacturing the wooden bridge consists of biomass fuel and crude oil. The biomass fuel consists of wood chips and sawdust from the saw mill, and used in the manufacturing of wood products for heating and wood drying. Crude oil is used mainly for transportation. Electric power is primarily nuclear (53 %) and hydropower (47 %).

The total primary energy use for manufacturing the wooden bridge is 4480 MJ/m^2, while the total primary energy use for the concrete bridge is 11636 MJ/m^2 (see Figure 11).

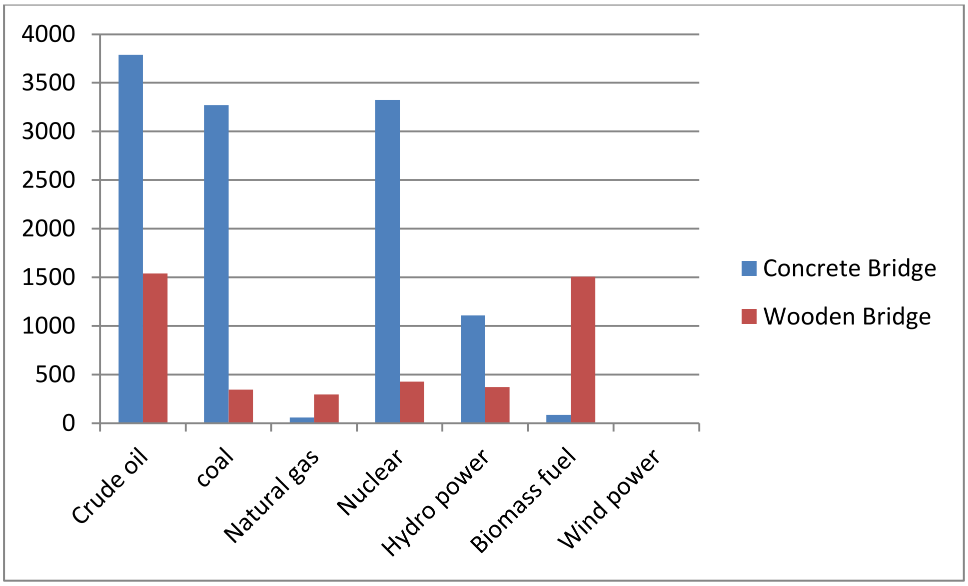


Figure 11. Total energy use for manufacturing of wooden bridge and concrete bridge

5.4.2-Air Emissions

The production phase is the main contributor to the total air emissions. Air emissions associated with the wooden bridge are dominated by carbon dioxide, which mostly comes from production of the steel hardware and wood products as well as from transportation. In the LCA of the wooden bridge biogenic based CO_2 emissions are considered as zero emission, since the forest cycle and the CO_2 uptake during tree growth are included in the total CO_2 balance.

The total CO_2 emission from manufacturing the wooden bridge is 14830 kg and the total CO_2 emission per square meter of the bridge is equal to 130 kg/m^2. In Figure 12, the emissions of CO_2 from different components and processes for the bridge are shown.

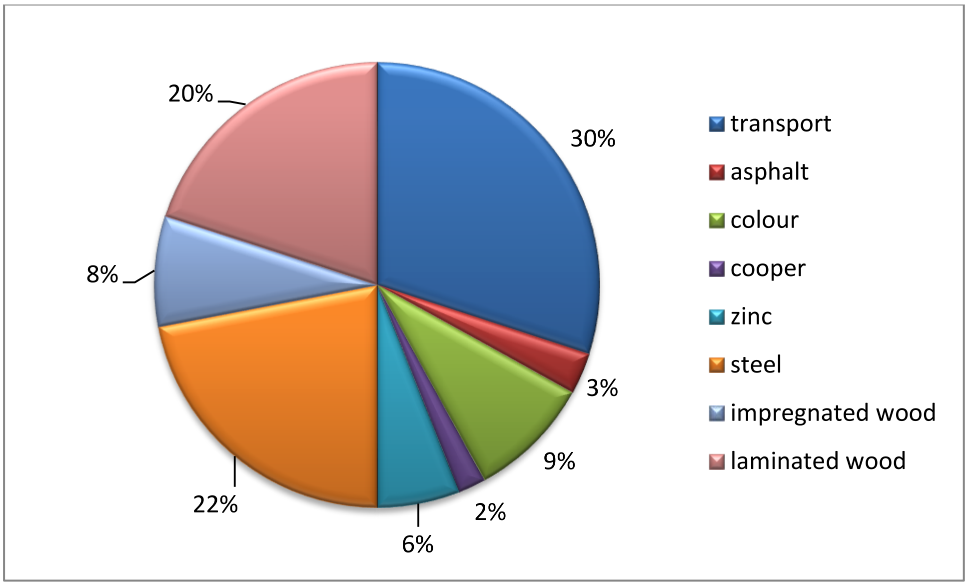


Figure 12. Share of CO_2 emissions from different component and processes in the wooden bridge

Maintenance or refurbishment during the use phase of the bridges results in emissions to the atmosphere. The concrete bridge cause CO_2 emission but on the other hand absorbs some CO_2 during the service life. Hence, concrete bridges are superior to wooden ones in this respect as they don't need maintenance in most cases.

Table 13 presents total amounts of CO_2 emissions from cradle to use phase for the two bridges in the case study.

Table 13. Total CO_2 emissions from cradle to use phase of the bridges

	Wooden Bridge	Concrete Bridge	Units
Total CO_2 emissions from manufacturing of the bridges	130	1082	kg/m^2
Total CO_2 emissions during use phase of the bridges	20	-15	kg/m^2
Total	**150**	**1067**	**kg/m^2**

There is no emission from waste handling of the wooden bridge, since carbon dioxide from combustion of biofuels is considered to have zero emissions and doesn’t contribute to global warming. However, there should have been some emissions from recycling of other materials like asphalt or steel. If the first scenario of waste handling of the concrete bridge is applied, owing to landfilling of the concrete is rare, then Table 14 represents the result of comparing total CO_2 emissions from cradle to grave of the bridges.

Table 14. Total CO_2 emissions from cradle to grave of the bridges

	Wooden Bridge	Concrete Bridge	Units
Total CO_2 emissions from cradle to grave for the bridges	150	1030	kg/m^2

It can be understood straightforwardly from Table 13 and Table 14, the significant difference between CO_2 emissions from wooden bridge and concrete one. There are some reasons for this large difference such as LCA of wooden bridge has been done based on different assumptions; moreover CO_2 uptake by growing trees has been included in the LCA of the wooden bridge. Hence total CO_2 emissions from manufacturing of the wooden bridge will decrease considerably. Wood industries argue that as their raw materials are from trees which have the capability of CO_2 absorption, their products will be more environmentally friendly based on total greenhouse gas emissions. However, it is not fully true, as they deprive the nature of plants that could have CO_2 absorption for a longer span, even if wooden industries replace the cut trees with new ones.

6. Cradle to grave model of a virtual concrete bridge

In this section, a life cycle assessment (LCA) model of a virtual concrete bridge has been developed in KCL-ECO to compare environmental impacts of a virtual bridge with that of the wooden bridge in section 5.3. The virtual bridge has the same size as the wooden one and also their purpose of use is the same.

The reason for designing a virtual bridge is to show how different assumptions can affect the results of comparison. In addition, in order to have more precise comparative LCAs, it is better to have bridges with the same sizes. Therefore, the functional unit has been defined as one pedestrian bridge with a total length of 46 m, a width of 2.5 m, a span of 45.5 m and with a total life time of 80 years.

(Notice: in this study ''virtual concrete bridge'' is termed as just ''virtual bridge''.)

6.1-Methodology

The LCA model of the virtual bridge was developed from cradle to grave to calculate total CO_2 emissions and total energy consumption. CO_2 uptake during use phase and demolition has been calculated and considered in the total CO_2 balance.

The LCA model of the virtual bridge uses some assumptions; the manufacturing conditions of the virtual bridge and materials use are the same as for the concrete bridge in section 4.2, the life cycle assessment covers only the surface of the bridge, the bridge has 2 cassettes under the surface and 6 beams under the cassettes. This is since Pousette (1998) just considered the wooden superstructures in the LCA of the wooden bridge.

Therefore, the total volume of the bridge measured is 66 m^3 with inclusion of steel reinforcements.

The service life of the virtual bridge is twice that of the wooden one; hence emissions and energy consumption related to the wooden bridge should be multiplied by two.

6.2-Results of the LCA of the virtual concrete bridge

Total amounts of materials consumed to manufacture the virtual bridge are tabulated in Table 15.

Table 15. Amounts of materials required for manufacturing of the virtual bridge

Raw materials		Units	Amounts	Sum
Cement	CEM I	ton	9	24
	CEM II		15	
Concrete	on-site	ton	162	268

weight	cast concrete			
	precast concrete		106	
Concrete volume	on-site cast concrete	m^3	22	66
	precast concrete		44	
Steel reinforcements	on-site cast concrete	ton	3	3.5
	precast concrete		0.5	

Of the total volume of the concrete 35 % of the bridge is made from on-site cast concrete.
Total electric power needed to manufacture the bridge is 34 GJ.
Table 16 shows the most important processes from an energy point of view, their amounts and proportions.

Table 16. Use of electric power in different process steps

Processes	Amounts (GJ)	Percentage (%)
Concrete product production (on-site casting)	10	29
Concrete production (on site casting)	1	3
Steel production-EAF (Swedish recycled)	7	21
Precast production	10	29
Production of crushed aggregates	2	6
CEM I production	1	3
Raw meal to produce clinker	1	3
Clinker production	1	3
Others	1	3
Total	**34**	**100**

Table 17 indicates the amounts of primary energy resources used to manufacture the virtual bridge.

Table 17. Primary energy resources used to manufacture the virtual bridge

Primary energy resource use	Amounts (GJ)
Coal	52
Crude oil	105
Natural gas	3
Nuclear power	65
Biomass fuel	2
Hydropower	22
Wind power	0.1
Total	**249.1**

Total CO_2 emissions from entire life cycle of the virtual bridge have been divided into three groups, CO_2 emissions from raw materials, fossil based CO_2 emissions, and biogenic based CO_2 emissions. The definition of each type of CO_2 emission can be found in section 4.2.4.

Figure 13 shows total amount of CO_2 emissions from cradle to use phase of the virtual bridge, Figure 14 and Figure 15 show total CO_2 emissions from cradle to grave by considering first scenario of waste handling for the bridge (see section 4.3.1) and second scenario of waste handling for the bridge (see section 4.3.2) respectively. Concrete carbonation has been calculated through use phase and also during end of life treatments.

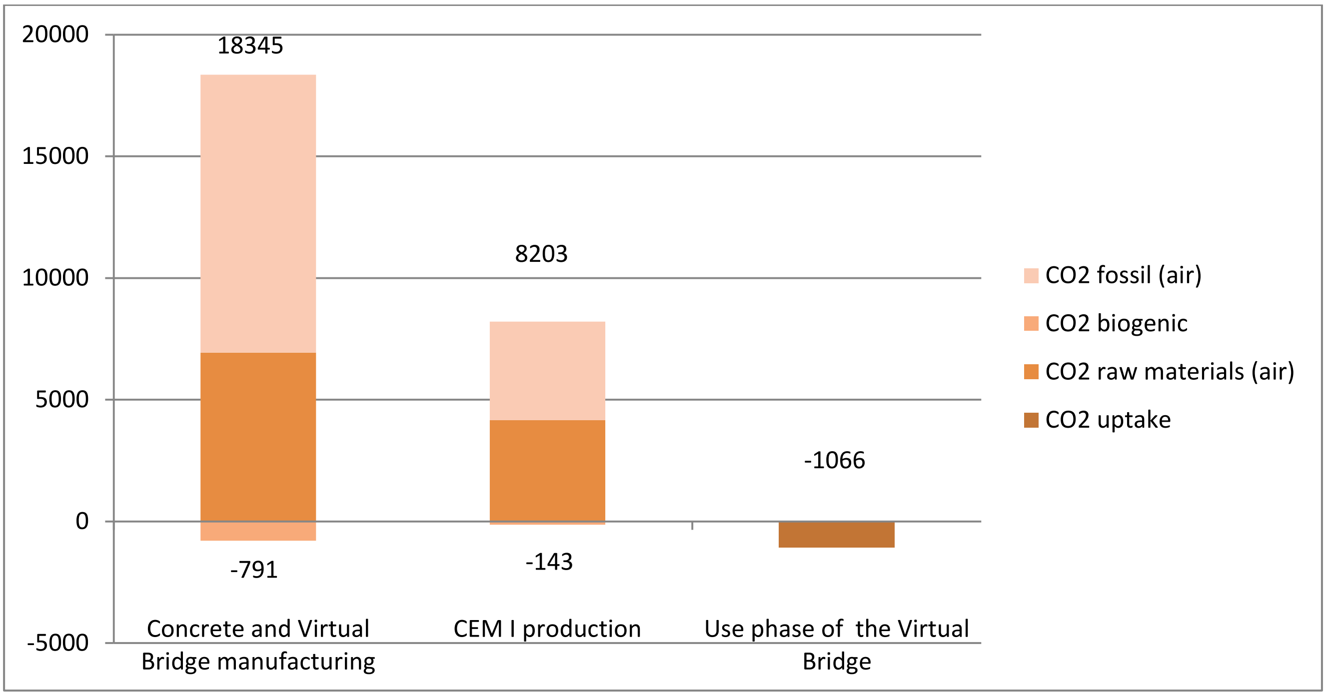


Figure 13. Total CO_2 emissions (kg) and uptake (kg) from ''cradle to use phase'' of the virtual bridge, shown divided into different process steps. The biogenic CO_2 emissions are contributed from biomass and waste fuels therefore they are considered as zero emissions, their amounts are shown in the figure as additional information.

The highest amount of CO_2 emissions originates from concrete and virtual bridge manufacturing. 35 % of the total volume of the bridge is made from on-site cast concrete, therefore a lower amount of CEM I needed. As a result, CEM I production contributes to less CO_2 emissions. The rest of the bridge is made from precast concrete, hence a higher amount of CEM II needed.

According to Figure 13, regarding the total CO_2 uptake, total CO_2 emissions released by raw materials decrease from 11098 kg (6935 + 4163) to 10033 kg (6935 + 4163 - 1066), corresponding to 10 % reduction. CO_2 uptake during the use phase is considerable compared to total CO_2 emissions from raw materials.

The total CO_2 emissions from cradle to use phase of the virtual bridge is 25482 kg (Total CO_2 emissions from CEM I production + Total CO_2 emissions from concrete and virtual bridge manufacturing – CO_2 uptake during use phase).

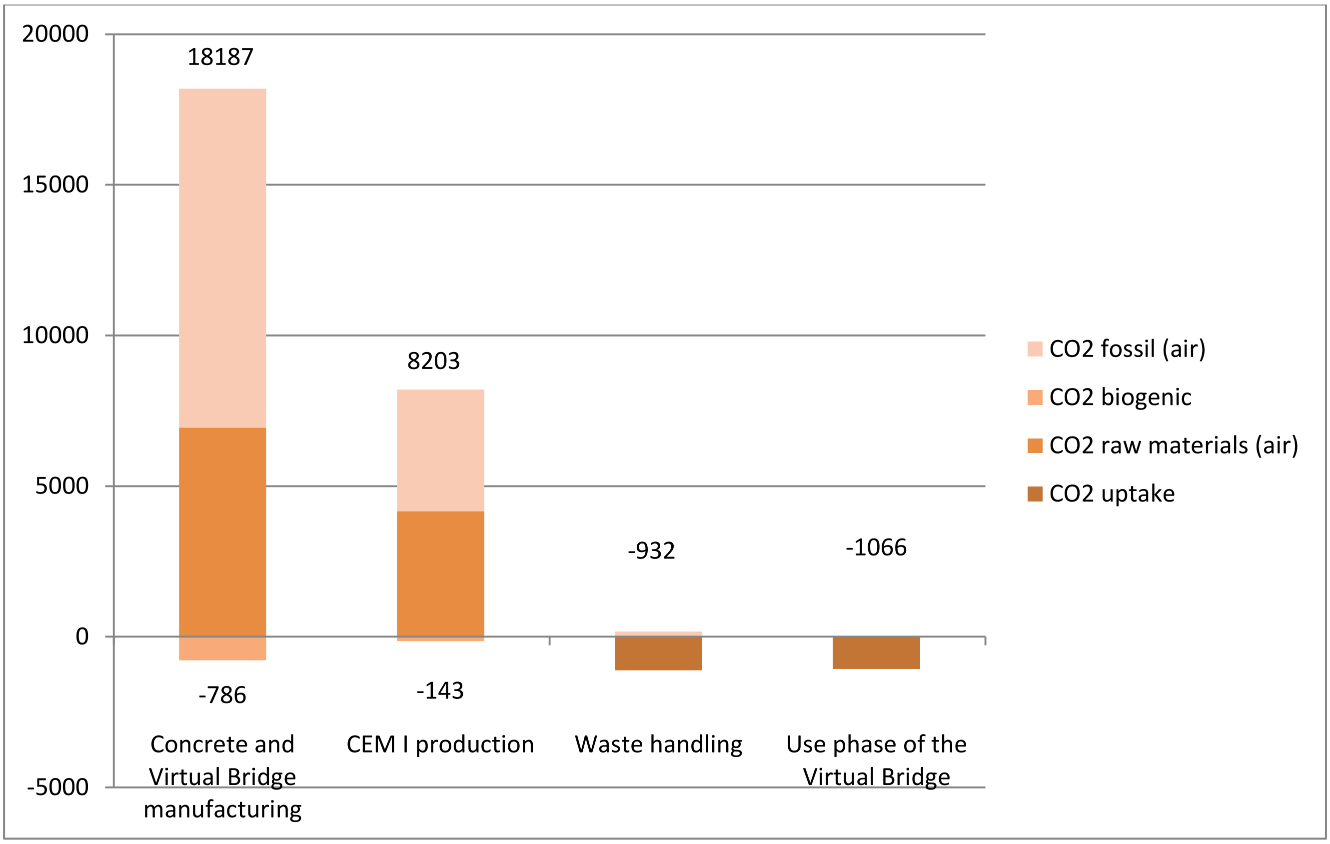


Figure 14. Total CO_2 emissions (kg) and uptake (kg) for the virtual bridge from ''cradle to grave'' related to the first scenario of waste handling, shown divided into different process steps. The biogenic CO_2 emissions are contributed from biomass and waste fuels therefore they are considered as zero emissions, their amounts are shown in the figure as additional information.

According to the results of the first scenario of waste handling, the CO_2 emission from raw materials reduces from 11098 kg to 8923 kg (6935 + 4163 – 1066 - 1109), about 20 % reduction. Fossil CO_2 and biogenic CO_2 emissions have almost the same pattern as in Figure 13.

The total CO_2 emissions measured is 24392 kg (Total CO_2 emissions from CEM I production + Total CO_2 emissions from concrete and virtual bridge manufacturing – CO_2 uptake during use phase – CO_2 uptake during waste handling).

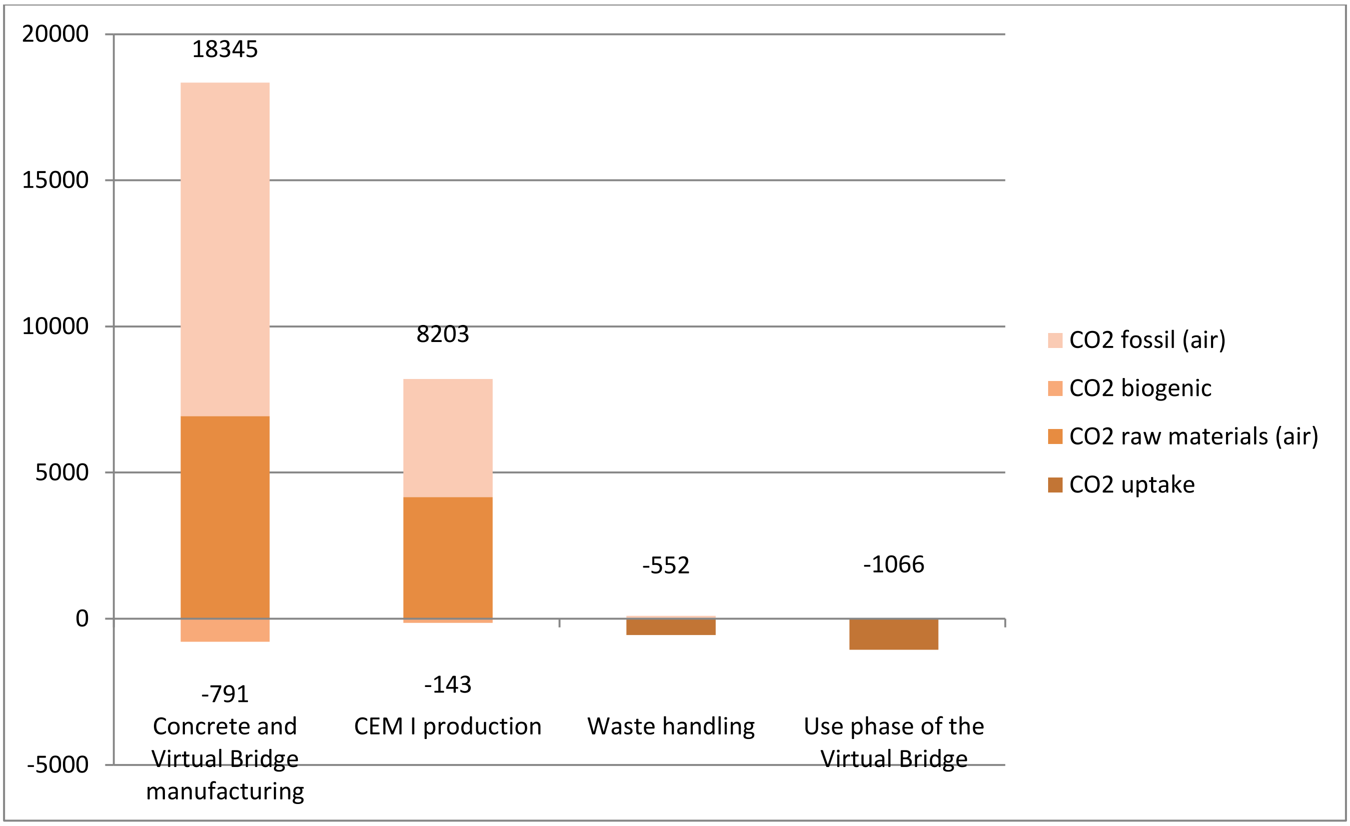


Figure 15. Total CO_2 emissions (kg) and uptake (kg) for the virtual bridge from ''cradle to grave'' related to the second scenario of waste handling, shown divided into different process steps. The biogenic CO_2 emissions are contributed from biomass and waste fuels therefore they are considered as zero emissions, their amounts are shown in the figure as additional information.

It can be seen from Figure 15, regarding the total CO_2 uptake, the total CO_2 emissions from raw materials are reduced from 11098 kg to 9480 kg (6935 + 4163 – 1066 - 552), about 15 %.
The amounts of fossil CO_2 emission and biogenic CO_2 emission do not change compared to Figure 13.
The total CO_2 emissions measured are 24930 kg (Total CO_2 emissions from CEM I production + Total CO_2 emissions from concrete and virtual bridge manufacturing – CO_2 uptake during use phase – CO_2 uptake during waste handling).

6.3-Comparison of wooden bridge and virtual concrete bridge

In this section, results from section 6.2 will be compared with the LCA results of wooden bridge to show which construction material has better environmental performance according to total CO_2 emissions and energy consumptions. The functional unit which is considered is one bridge with a total service life of 80 years.

6.3.1-Fuel consumption

The total primary energy consumption for manufacturing the wooden bridge is 515222 MJ, while the total energy consumption for manufacturing the virtual bridge is 247128 MJ.
The total amount of energy needed for manufacturing the wooden bridge is twice as high as that of the virtual bridge (see Figure 16).

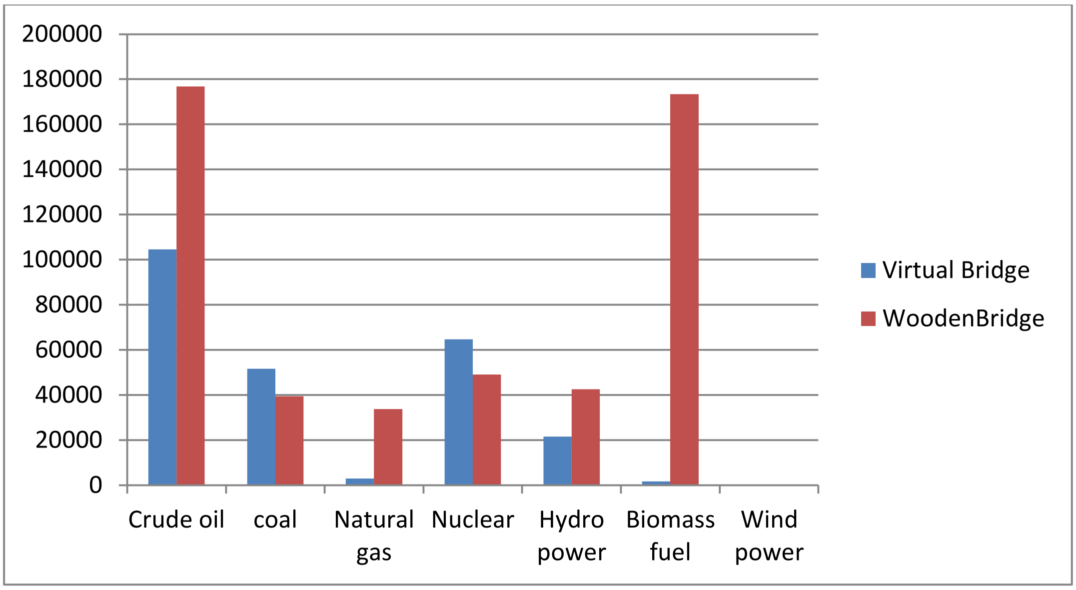


Figure 16. Total energy use for manufacturing the wooden bridge and virtual bridge

6.3.2-Air Emissions

Table 18 presents total amount of CO_2 emissions from cradle to use phase for two bridges in the case study.

Table 18. Total CO_2 emissions from cradle to use phase of the bridges

	Wooden Bridge	Virtual Bridge	Units
Total CO_2 emissions from manufacturing of the bridges	14830	26548	kg
Total CO_2 emissions during use phase of the bridges	2300	-1066	kg
Total	**17130**	**25482**	**kg**

There is no emission from waste handling of the wooden bridge, since combustion of biofuels is considered as zero emission to the atmosphere. If the first scenario of waste handling of the concrete bridge is applied, owing to landfilling of concrete is rare, then Table 19 represents the result of comparing total CO_2 emissions from cradle to grave of the bridges.

Table 19. Total CO_2 emissions from ''cradle to grave'' of the bridges

	Wooden Bridge	Virtual Bridge	Units
Total CO_2 emissions from cradle to grave for the bridges	17130	24392	kg

According to the results, the virtual bridge requires less energy, whereas the wooden bridge emits less CO_2.

It is obvious that the large differences between total CO_2 emissions from wooden bridge and concrete bridge (see section 5.4.2), and also between the amounts of energy consumptions of two bridges (see section 5.4.1) decrease considerably in this comparison between the wooden bridge and the virtual bridge. One of the main reasons is that the life cycle assessment of the virtual bridge covers similar assumptions as for the wooden bridge.

However, there is still uncertainty about the amount of CO_2 emissions from the life cycle of the wooden bridge, since forest is included in the LCA of the wooden bridge and considered as a benefit of the wooden bridge. Moreover, there should have been some amounts of CO_2 emissions from recycling of materials such as asphalt and steel in waste handling for the wooden bridge.

7-Conclusion

In this study a streamlined life cycle assessment (LCA) of Portland cement, CEM I 42.5 N-SR3 MH/LA produced in Degerhamn, has been developed using the LCA software KCL-ECO to determine total CO_2 emissions and energy consumption for production of 1 ton of CEM I. The results show that, the cement production process is energy intensive. The main energy (fuels) consumption is related to the clinker production process in the kiln.

In order to reduce energy consumption from cement production, the main attention should be on the clinker kiln. The Degerhamn plant is not an effective plant from an energy point of view due to being an old plant and constructed without cyclone towers.

One of the possible technologies for the near future in cement plants is to adjust them to recover waste heat from the kiln.

Besides energy reduction and saving, one of the concerns is to conserve fossil fuel resources. Renewable energy resources such as biomass not only can save fossil fuel resources, but also can reduce the greenhouse gas impacts resulting from fossil fuels. The main fossil CO_2 emissions are from calcination of limestone and fuel consumption in the clinker kiln. Increasing use of biomass fuels in the kiln leads to biogenic emission that is considered as zero emission, due to the corresponding CO_2 absorption during the growth of biomass.

In addition to changing the energy (fuels) resource use from non-renewable to renewable, changing the content of clinker in cement and using alternative materials will decrease fossil CO_2 emissions.

All of the above recommendations may be difficult to be implemented and need advanced technologies but they can be used as a guideline for future work.

One of the applications of CEM I, is using it in heavy constructions such as bridges which have high requirements of durability.

A Life cycle assessment (LCA) model of a concrete bridge was successfully developed in KCL-ECO to identify total CO_2 emissions and energy consumption.

The results show that large amounts of CO_2 are emitted and that energy consumption is high when a concrete bridge has a massive construction. The main CO_2 emission is from CEM I production. Energy consumption is mainly from steel production, on-site cast concrete production, and on-site cast concrete products such as surface, columns, foundations and walls, since 86 % of total volume of the bridge is made of ready mixed or on-site cast concrete.

One of the important processes that take place in the use phase of the concrete products is CO_2 uptake or carbonation. CO_2 uptake is the reverse reaction of calcination of limestone in the kiln. According to the concrete products, the rate of carbonation varies during the service life of the products. Due to the small surface area of a compact bridge, the total CO_2 uptake is small compared to total CO_2 emissions from calcination of limestone. For such constructions like bridges, maximum CO_2 uptake potential remains for end of life treatments.

According to two different scenarios for waste handling of the concrete bridge, crushing of demolished concrete and storing it to accelerate CO_2 uptake should be preferred to landfilling of the demolished concrete, since landfilling of the demolished concrete is done without steel and concrete recycling processes. Moreover, results show that total CO_2 uptake from first scenario is higher than the second one.

It is necessary to decrease the amount of energy use for waste handling of the concrete bridge, and improve some methods to increase total CO_2 uptake. In this case recycling of steel reinforcements and crushed concrete helps to offset energy required to crush the demolished concrete.

This study has aimed to compare climate and energy performance of a concrete bridge with that of a wooden bridge, for that reason the wooden bridge in section 5.3 has been chosen.

LCA of the wooden bridge shows that air emissions in the wooden bridge are dominated by carbon dioxide. Production of materials needed for bridge manufacturing is the main contributor to total CO_2 emissions.

A comparison of wooden bridge and concrete bridge during their entire life cycle shows that wooden bridge has lower CO_2 emission and lower energy consumption.

It should be taken into consideration that the wooden bridge and the concrete bridge had different configurations (shape, size, and foundation) and therefore were difficult to compare. The wooden bridge analysis covered only wooden superstructures and CO_2 absorption during the tree growth are included in total CO_2 emissions from manufacturing of the bridge, which leads to significant decrease in total CO_2 emissions.

In order to increase the accuracy of the comparison and have similar assumptions as the wooden bridge, an LCA model of a virtual concrete bridge, with the same construction conditions as the concrete bridge but with similar shape as the wooden bridge, was developed in KCL-ECO. Analysis of the virtual bridge covers only surfaces, cassettes under the surface, and beam under the cassettes.

The results show that different assumptions cause highly different results and significant differences between CO_2 emissions and energy consumptions from the virtual bridge and the concrete bridge.

Comparing LCA of the virtual bridge with that of the wooden bridge shows that, the virtual bridge consumes half of the energy compared to the wooden bridge, whereas, CO_2 emission from the wooden bridge is less than that of the virtual bridge. There are still uncertainties about the total CO_2 emissions from wooden bridge. It will result in much higher amount of CO_2 emissions if CO_2 uptake during tree growth is not included.

It should be taken into account that, it is not straightforward to generalize the results of one study about all types of bridges. Depending on the applications and purposes designers and constructors are looking for, they can decide to choose wood or concrete. For example if there is demand for bridges with higher durability and no maintenance concrete is a suitable construction material. Moreover CO_2 uptake or carbonation of the concrete is another advantage that increases the popularity of the concrete.

To sum up, the comparison of climate and energy performance of the bridges in this study was more complicated than expected.

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Appendices

Appendix A- KCL-ECO models

Use zoom function in the computer to look at the entire model

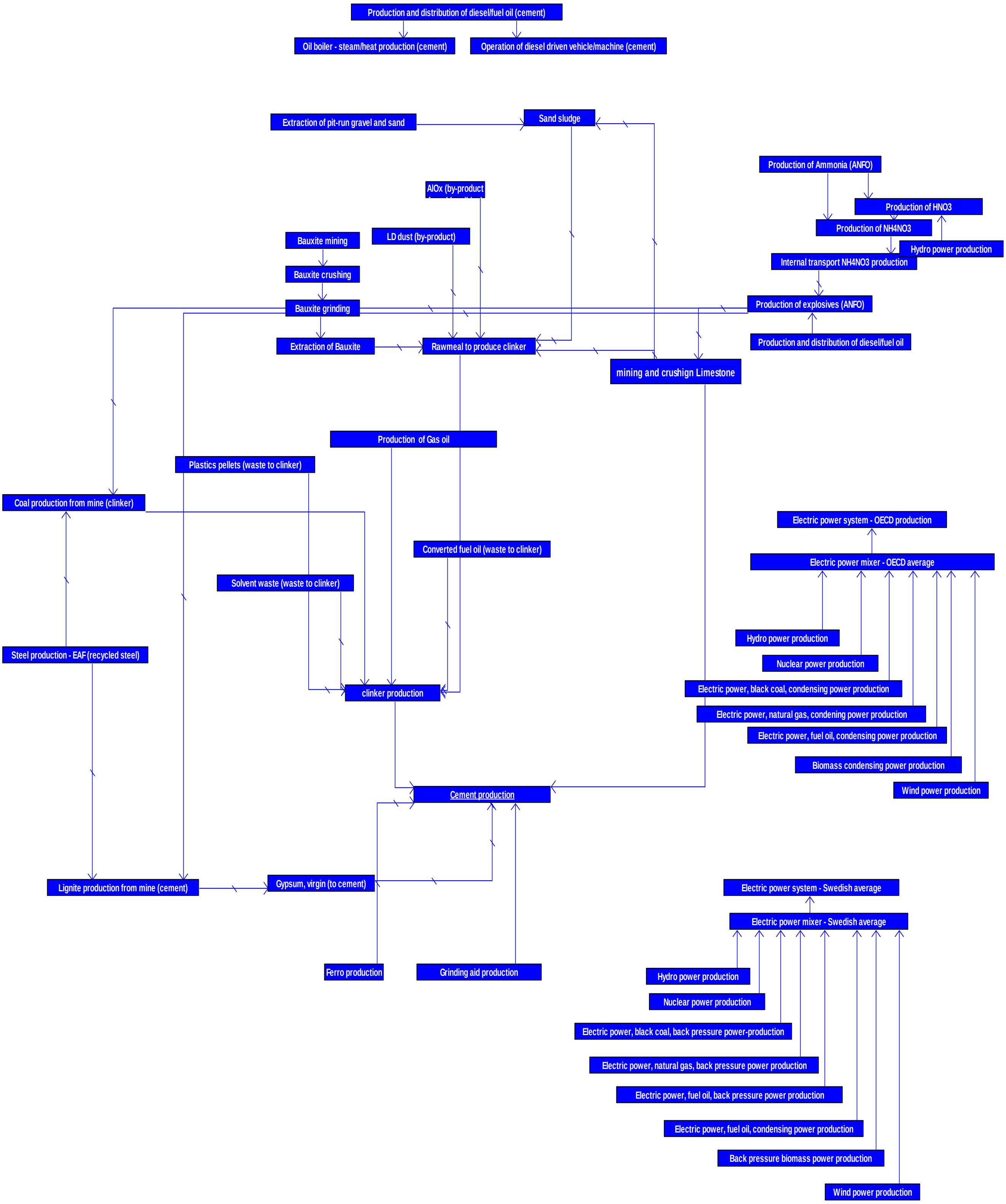


Figure 1. Cradle to gate model of Portland cement

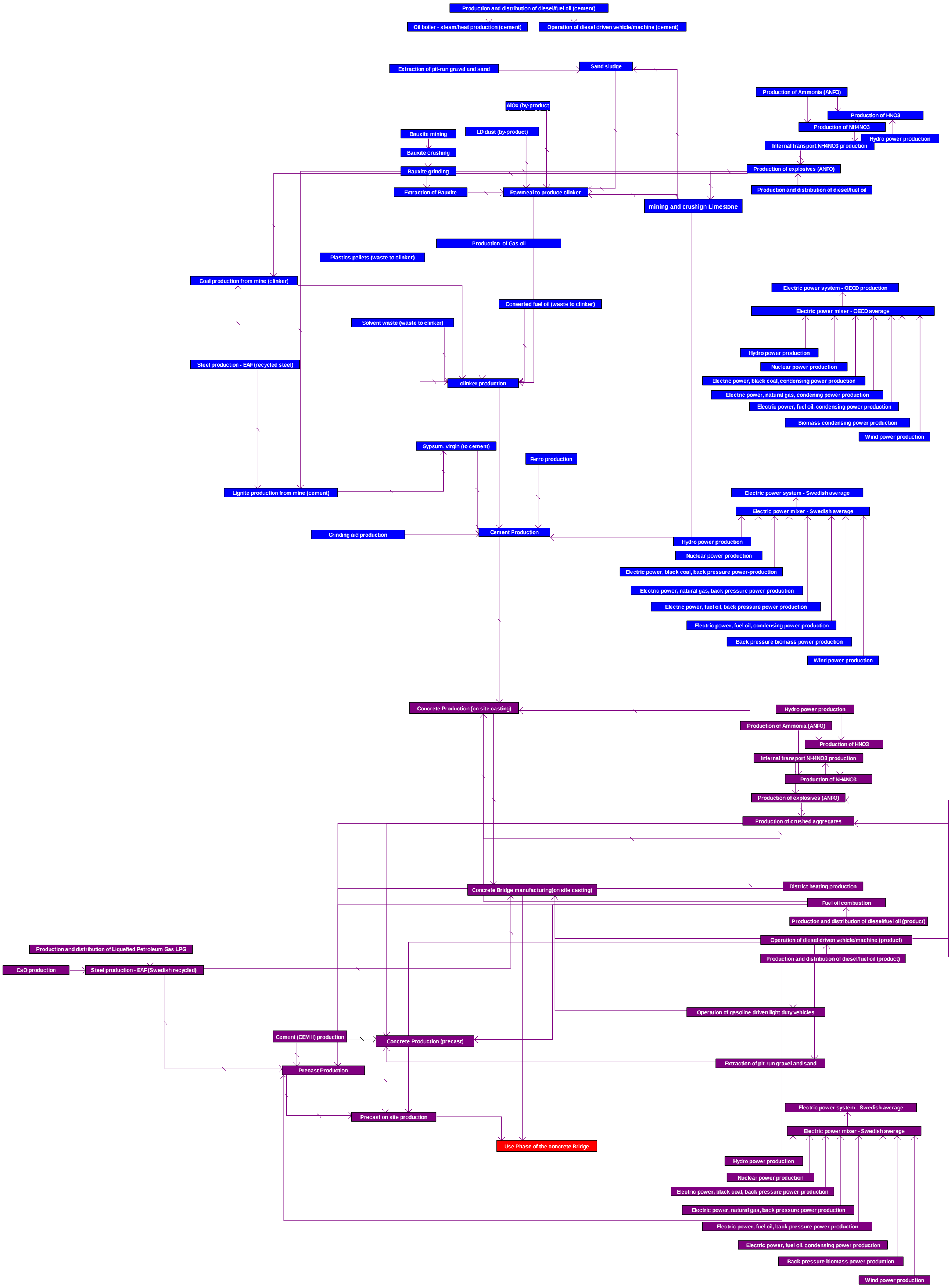


Figure 2. Cradle to use phase model of the concrete bridge

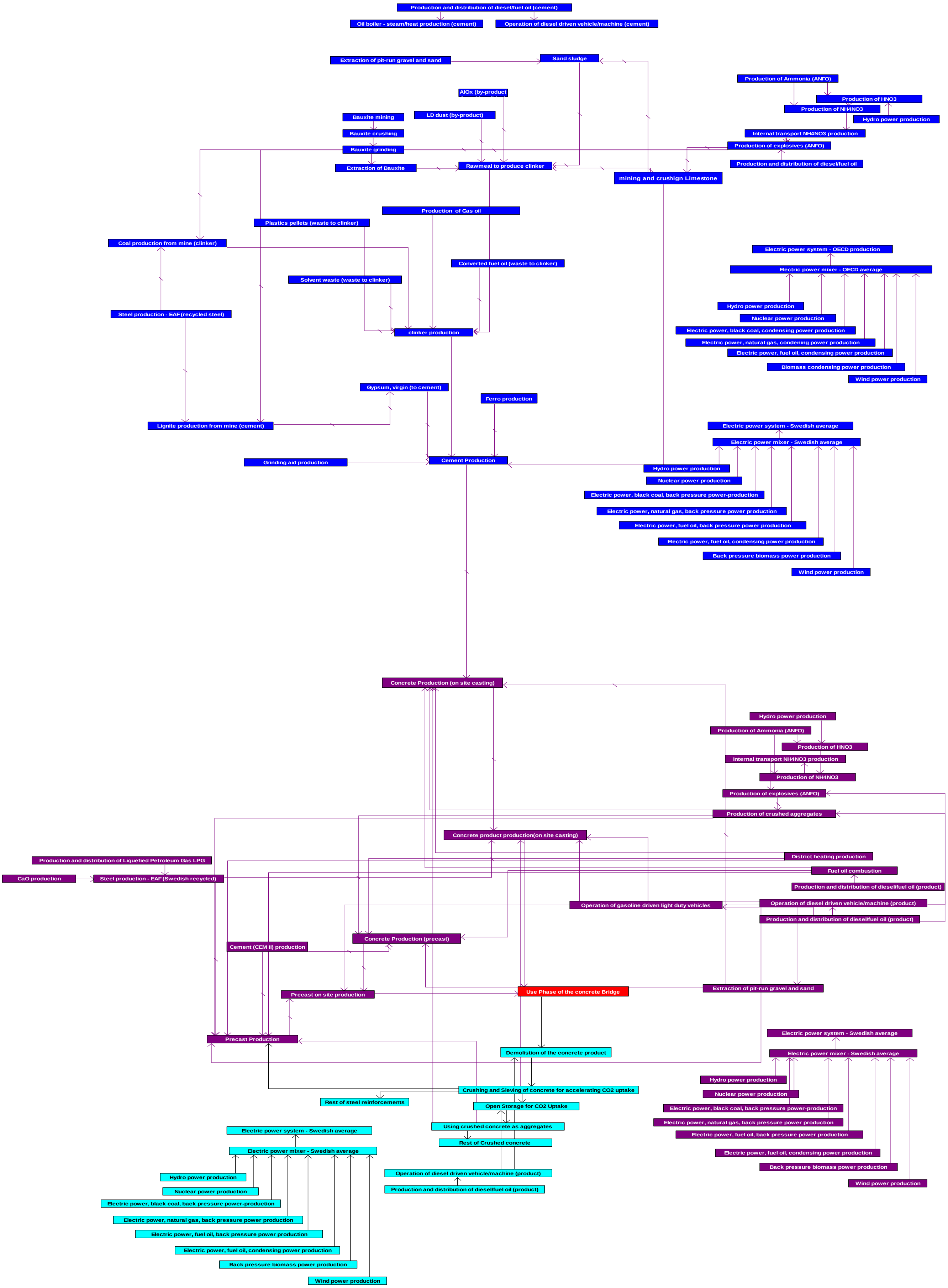


Figure 3a. Cradle to grave model of the concrete bridge- Scenario 1

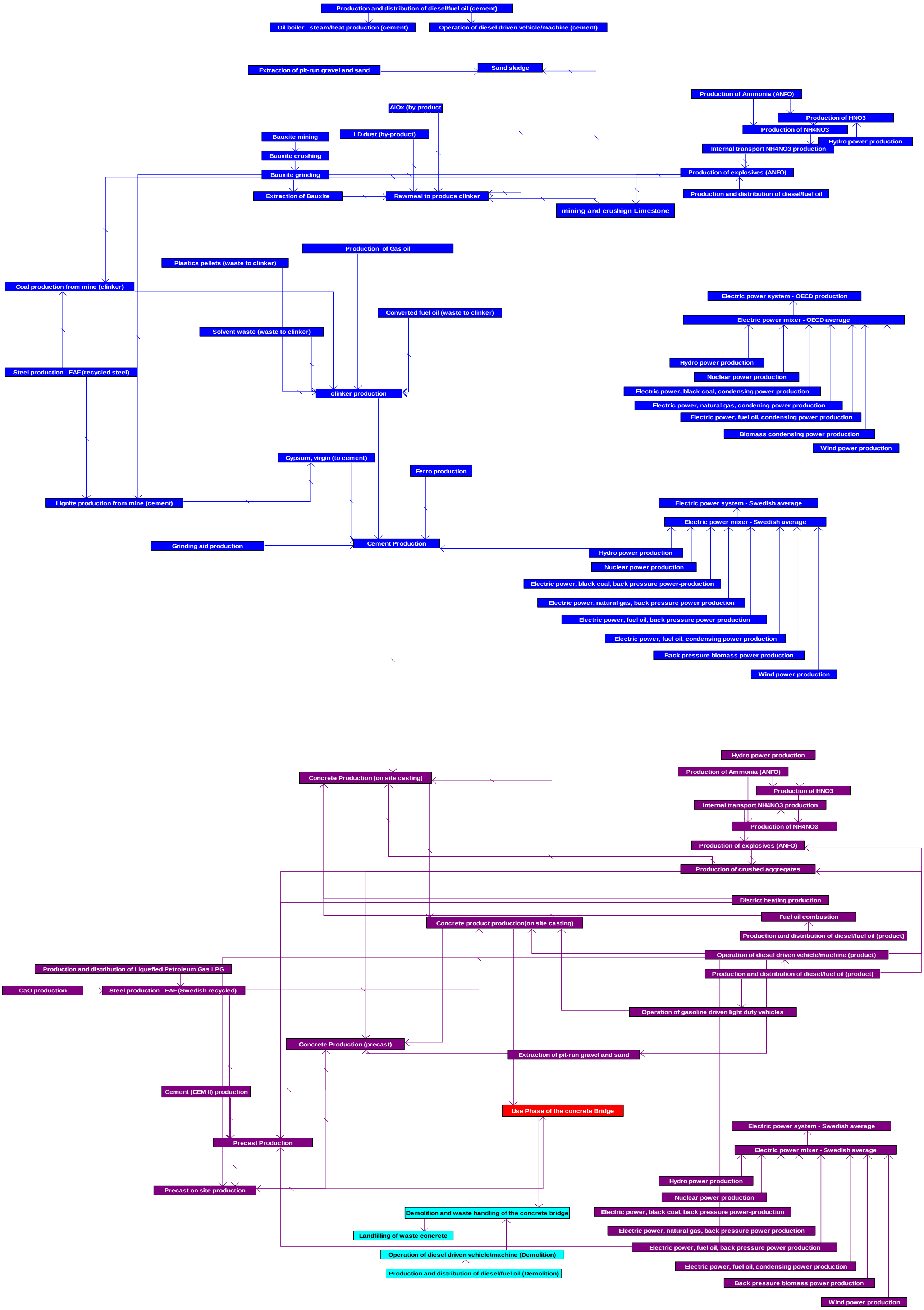


Figure 3b. Cradle to grave model of the concrete bridge- Scenario 2

Appendix B- different emissions from transports and manufacturing

Mode of transportation: heavy truck
Total load capacity: 40 ton
Energy resource non-renewable: crude oil= 0.57 MJ/km*ton

Table 1a. Data for heavy truck

Emissions to air	Amounts (kg/km*ton)
CO	6.5E-005
CO_2 fossil	0.041
HC	8E-005
NOx	0.0007
Particles	1.6E-005
SO_2	1E-005

Mode of transportation: Freight ship, 2000 - 8000 ton
Energy resource non-renewable: crude oil= 0.3 MJ/km*ton

Table 1b. Data for freight ship

Emissions to air	Amounts (kg/km*ton)
CO	1.5E-005
CO_2 fossil	0.013
HC	1.1E-005
NOx	0.00032
Particles	1.2E-005
SO_2	6.9E-005

Table 2. Total emissions to air from manufacturing the Portland cement

Emissions	(Kg per 1000 kg CEM I produced)
CH_4	0.156
CH_4(CO_2 equivalent)	3.57
CO	0.016
Dust	0.064
N_2O	0.0067
N_2O(CO_2 equivalent)	1.97
NOx	2.089
SO_2	0.039
SOx	0.024

Table 3. Total emissions to the air for construction the bridge

Emissions	(Kg per manufacturing the bridge)
CH_4	46.78
CH_4(CO_2 equivalent)	1039
CO	107
Dust	18
N_2O	5.12
N_2O(CO_2 equivalent)	1206

NOx	1244
SO_2	58
SOx	6.4

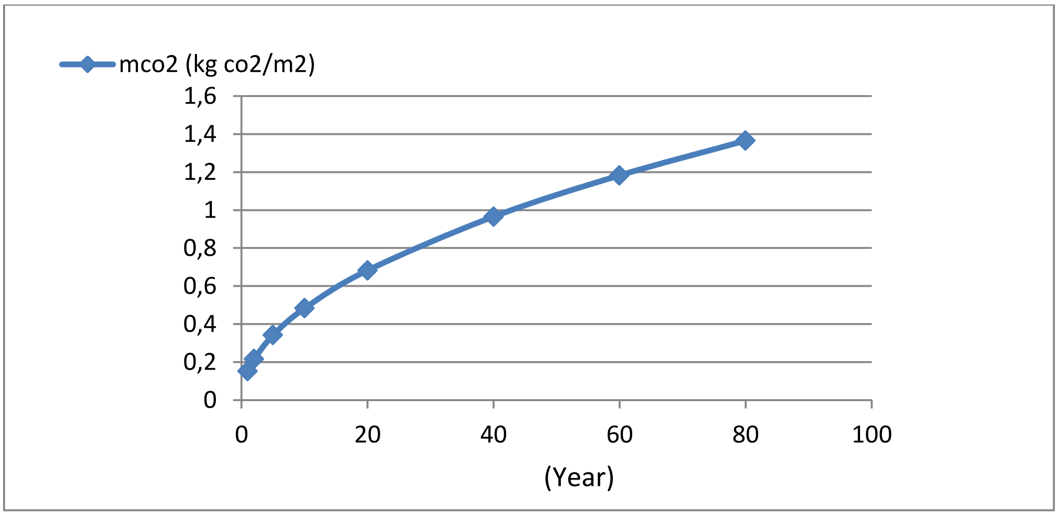
Appendix C- CO2 uptake of the bridge

1-Parts exposed to rain

Assumptions:

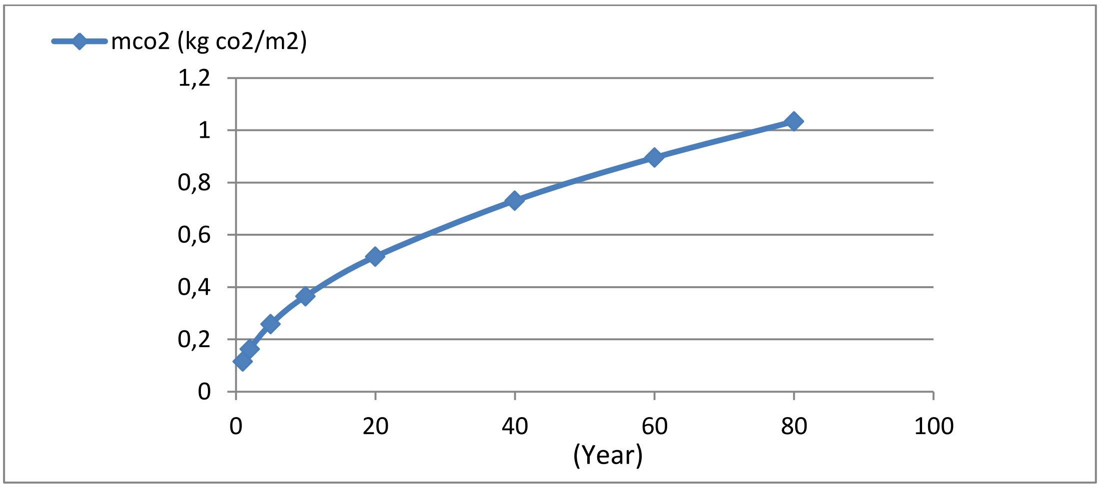
Type of the cement: CEM I
Cement content: C=420 kg/m3
Degree of carbonation= 0.75
Carbonation rate factor: K= 1 mm/√year
The amount of CaO per weight of Portland cement: CaO/C=0.62
M_{CO2}= 44.01 kg/mole
M_{CaO}= 56.08 kg/mole

Time	(Year)	1	2	5	10	20	40	60	80
Depth(dc)	(mm)	1	1.41	2.24	3.16	4.47	6.33	7.75	8.94
m_{CO2}	(kg CO_2/m^2)	0.15	0.22	0.34	0.48	0.68	0.97	1.18	1.37



And
Type of the cement: CEM II
Cement content: C=350 kg/m3
Degree of carbonation= 0.75
Carbonation rate factor: K= 1.1 mm/√year
The amount of CaO per weight of Portland cement: CaO/C=0.51
M_{CO2}= 44.01 kg/mole
M_{CaO}= 56.08 kg/mole

Time	(Year)	1	2	5	10	20	40	60	80
Depth(dc)	(mm)	1.1	1.56	2.46	3.48	4.92	6.96	8.52	9.84
mco2	(kg co2/m2)	0.12	0.16	0.26	0.37	0.52	0.73	0.89	1.03



2-Parts sheltered from rain

Assumptions:

Type of the cement: Anläggnings Cement

Cement content: C=420 kg/m3

Degree of carbonation= 0.75

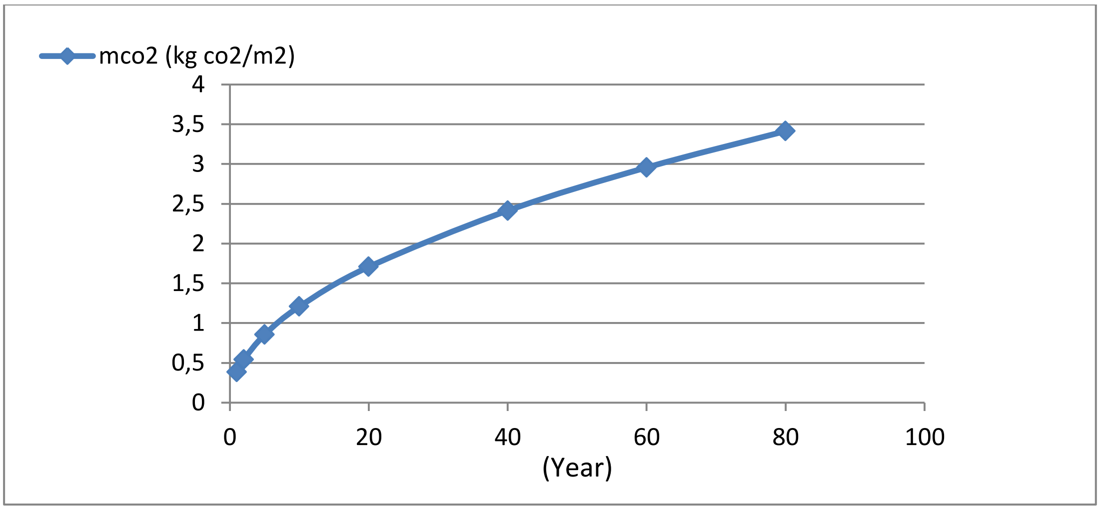
Carbonation rate factor: K= 2.5 mm/√year

The amount of CaO per weight of Portland cement: CaO/C=0.62

M_{CO2}= 44.01 kg/mole

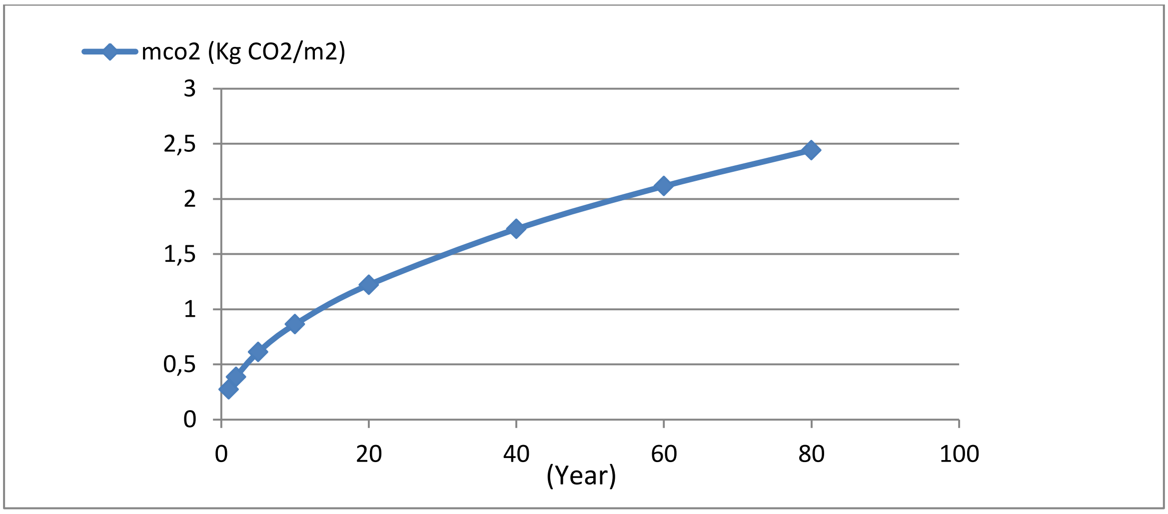
M_{CaO}= 56.08 kg/mole

Time	(Year)	1	2	5	10	20	40	60	80
Depth(dc)	(mm)	2.5	3.54	5.59	7.91	11.18	15.81	19.36	22.36
m_{CO2}	(kg CO_2/m^2)	0.38	0.54	0.85	1.21	1.71	2.41	2.96	3.41



And
Type of the cement: CEM II
Cement content: C=350 kg/m3
Degree of carbonation= 0.75
Carbonation rate factor: K= 2.6 mm/√year
The amount of CaO per weight of Portland cement: CaO/C=0.51
M_{CO2}= 44.01 kg/mole
M_{CaO}= 56.08 kg/mole

Time	(Year)	1	2	5	10	20	40	60	80
Depth(dc)	(mm)	2.6	3.68	5.81	8.22	11.63	16.44	20.14	23.26
mco2	(Kg CO2/m2)	0.27	0.39	0.61	0.86	1.22	1.73	2.12	2.44



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