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CO_2 Uptake During the Concrete Life Cycle

Guidelines

- Uptake of carbon dioxide in the life cycle inventory of concrete

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Title: **Guidelines - Uptake of carbon dioxide in the life cycle inventory of concrete**

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PREFACE

The objective of this project, of which this report is a part, is to provide documentation of concrete carbonation during service life and secondary use. This documentation should be used for environmental assessment of concrete buildings and structures, and to evaluate the effect of concrete carbonation on the overall CO_2 emissions from cement and concrete production in the Nordic countries.

Approximately half of the CO_2 emission from cement production stems from the calcination of limestone, i.e. a process where limestone is burnt and CO_2 gas is released to the atmosphere. Theoretically, hardened concrete binds approximately the same amount of CO_2 in a process called carbonation. The concrete's ability to bind CO_2 and the rate of the process depends on many variables, including the type of concrete and its application.

The methodology and the impact that concrete carbonation has in the assessment of CO_2 emissions from concrete has not been fully documented. Specifically, there is a lack of knowledge about the carbonation of demolished and crushed concrete. The existing models for calculating carbonation do not take into account that the concrete is crushed and recycled after use. Consequently, the contribution of the cement and concrete industry to net CO_2 emissions is strongly overestimated. This overestimation has a significant influence on CO_2 policy; on the criteria for environmental labelling; and on the selection of materials based on principles of environmentally correct design. A comparison of the environmental impacts from different building materials (e.g. concrete versus wood and steel) is at present unfair because of the lack of documentation of the CO_2 uptake in concrete.

The present report is one of five documents published during the project "CO_2 uptake during the concrete life cycle". Three reports cover the background data and the last two reports include the results of the project.

The background reports are:

- Carbon dioxide uptake during concrete life cycle, state of the art, published by Swedish Cement and Concrete Research Institute - CBI, www.cbi.se, ISBN 91-976070-0-2
- Information on the use of concrete in Denmark, Sweden, Norway and Iceland, published by Icelandic Building Research Institute, www.ibri.is, ISBN 9979-9174-7-4
- Carbon dioxide uptake in demolished and crushed concrete, published by Norwegian Building Research Institute, www.byggforsk.no, ISBN 82-536-0900-0

The reports with results are:

- Guidelines – Uptake of carbon dioxide in the life cycle inventory of concrete, published by Danish Technological Institute, www.teknologisk.dk, ISBN 87-7756-757-9
- The CO_2 balance of concrete in a life cycle perspective, published by Danish Technological Institute, www.teknologisk.dk, ISBN 87-7756-758-7

The participants in the project are:

Danish Technological Institute (Project Manager)
Aalborg Portland A/S (head of Steering Committee)
Norwegian Building Research Institute
Norcem A.S
Elkem ASA Materials
Cementa AB
Swedish Cement and Concrete Research Institute
Icelandic Building Research Institute

Financing partners are:

Nordic Innovation Centre
Aalborg Portland A/S
Norcem A.S
Cementa AB

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Abstract

During the production of Portland cement based products energy is consumed and consequently CO_2 is emitted to the atmosphere. Inherent to the production of Portland cement is the calcinations of limestone resulting in the emission of 44 kg CO_2 per 100 kg of pure limestone ($CaCO_3$) fed to the clinker kiln. However, once the Portland cement is used for concrete the concrete will start to undergo a carbonation process during which CO_2 will be taken up by the concrete. In the NICe project "CO_2 uptake during the concrete life cycle" the carbonation rate of different concrete types under various conditions has been assessed including the rate of carbonation during secondary life i.e. after demolition and crushing of the concrete. Also, the project estimated the annual production of various concrete types and products. The present “Guidelines - Uptake of carbon dioxide in the life cycle inventory of concrete” represents, based on the findings of the NICe project, an attempt to establish a generic procedure of CO_2 life cycle inventory that adequately includes all phases in the life and secondary life of any concrete product.

1. Introduction

This report shows some of the results from the project "CO_2 uptake during the concrete life cycle".

Changes in inputs and outputs of one single substance, carbon dioxide, will have the same relative change in the results of an assessment as well as an inventory. While assessments can be carried out according to various methods, it is here chosen to present the basic data for a life cycle inventory of carbon dioxide.

Given new data regarding uptake of carbon dioxide as inventory data means that this can be implemented in a balance of the green house effect. If a method for assessment gives the opportunity to compare the green house effect with measures of other environmental effects, this can be done.

It has been important to include the findings of carbon dioxide uptake in a life cycle framework according to the ISO-standards, 14040-43. Therefore, a chapter regarding the principles of LCA is focusing on system boundaries and data for the inventory.

When setting up guidelines for emissions and uptake of carbon dioxide, these two aspects are described. The goal is to point out all significant contributions to a CO_2-balance. Given the most important contributions, a set of guidelines on how to implement this in practice is described. The use of the guidelines is illustrated by 2 examples.

2. Methodology

This chapter describes the general principles as well as omissions and limitations used in the data set for emissions and uptake of carbon dioxide during the service life of a construction.

2.1 General aspects

The scope of this project is to outline changes in a life cycle inventory caused by uptake of carbon dioxide through carbonation of concrete during the service life and after demolition. Because of this scope, relevant issues for a construction such as reinforcement and surface treatment are not included.

All life cycle assessments are in principle based on a life cycle inventory of a product system. The changes in focus include only changes of input and output of one single substance - carbon dioxide. This substance only contributes to the green house effect. Therefore, to present data that can be included in various LCA-tools, it is chosen to present data for a life cycle inventory. The methodology for describing the changes in the carbon dioxide balance is based on ISO-standards 14040-43, primarily DS/EN ISO 14041.

By using these new data presented in this report, the original scope of a LCA of a construction, product or service will not change.

2.2 Definitions and system boundaries

When performing a LCA for a product system and assessing one or more parameters, the system boundaries are among the most important factors for the results.

The goal for this section is to define:

- A functional unit
- Technology used
- Interactions with other systems
- System boundaries
- Life cycle steps

2.2.1 The functional unit

The functional unit defines the service provided by the product. This includes a description of the function of the products, the quality, service life, design and other properties.

Examples of functional units can be:

Edge beam on highway bridge	Part of a bridge with a certain defined strength class. Service life is 70 years, and secondary life is 30 years. Weight of one unit is 502 kg.
1 m^2 of roof tiles	Roof tiles weigh about 42 kg per m^2. Service life is 50 years, and secondary life is estimated to 50 years.

2.2.2 Technology used

The level of technology is represented by the current Nordic building tradition.

2.2.3 Interactions with other systems

Looking at the life cycle for a concrete construction, it appears that there are several material streams coming from other product systems as well as material streams from the construction used in other product streams. The streams of materials that interact with other product systems are shown in Figure 2.1.

Fly ash and blast furnace slag

In the production of cement, fly ash from coal based electricity production or blast furnace slag from iron production are often used. These materials may substitute natural raw materials in clinker production or may substitute clinker in cement production. Fly ash and blast furnace slag are waste materials which are assumed to be landfilled, if they cannot be used otherwise. Fly ash and slag are also used as partial replacement for cement in concrete production.

The differences are therefore:

Either:	Or:
Landfill of fly ash / blast furnace slag and extraction of natural raw materials and the related transportation	Transportation of fly ash / blast furnace slag from site of origin to cement or concrete production and processing the material by grinding etc.

The energy consumption and the related emissions have to be assessed in a life cycle assessment. Nevertheless, it is the same amount of material that has to be transported in both situations, and it is assumed that on average it is about the same distance. In one situation extraction of natural raw materials is included, and in the other processing of the fly ash/blast furnace slag. In both situations the differences are in transportation, i.e. consumption of oil. For extraction and grinding the energy source may as well be oil.

It is assumed that only minor errors are introduced by the choice of including "Transportation of fly ash / blast furnace slag from site of origin to cement or concrete production and processing the material by grinding etc."

Alternative energy sources

A variety of organic waste materials are used as alternative energy sources to ordinary energy resources. The most used conventional energy resources are coal, oil and natural gas. When burning these, carbon dioxide is released. When using renewable resources such as wood and other biological by-products the burning of these materials are CO_2 neutral. When using waste materials based on oil and gas, as for instance rubber and plastic products, the picture is not clear. If these waste products were landfilled, no carbon dioxide would have been released. If the waste products were incinerated and the energy utilised, the waste materials substitute a certain amount of conventional energy resources.

It is common in European life cycle inventory to use the energy content in waste materials, thus the carbon dioxide emissions from waste materials from non-renewables have to be included in the CO_2-balance.

Demolished concrete

Recycled concrete aggregates (RCA) processed from demolished concrete has a value for other purposes, for instance in road construction.

RCA may substitute sand, gravel and other similar natural materials. Demolished concrete has to be landfilled, if it cannot be used otherwise.

The differences are therefore:

Either:	Or:
Landfill of demolished concrete and extraction of sand, gravel etc. and the related transportation	Transportation and crushing demolished concrete from site of origin to site of use

Generally, it is an advantage for the environment, if the material can be reused and other natural materials preserved. Preservation of land and potential leakage from landfilled concrete is presently not easy to include in an inventory.

The difference between the two situations regarding emissions of carbon dioxide is related to the consumption of energy. It is assumed that reusing demolished concrete requires more energy than landfilling and extraction of new resources, although extraction of new materials may require blasting and crushing of bedrock. It is therefore chosen to include the reuse of concrete and the necessary processes for crushing and transportation.

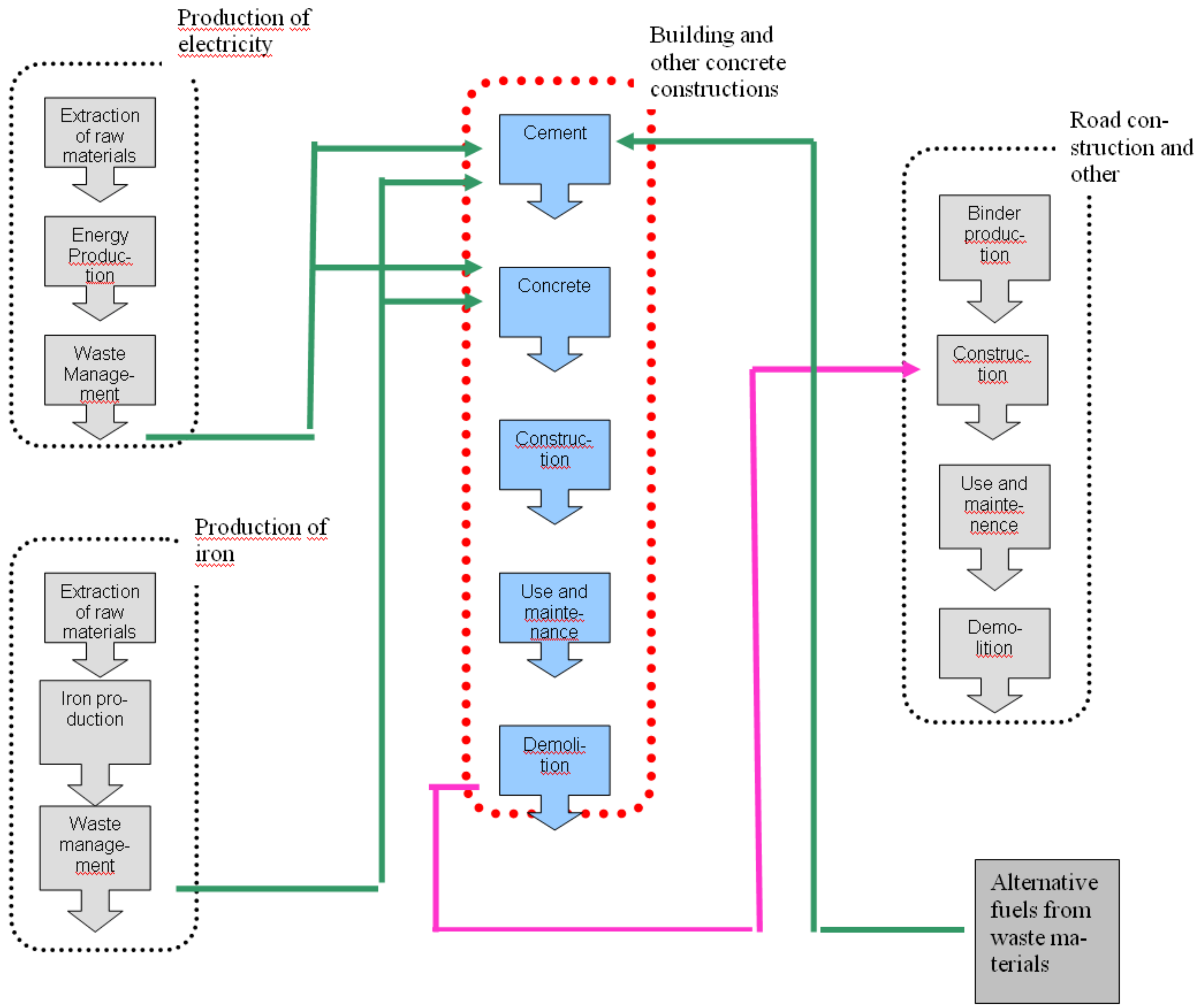
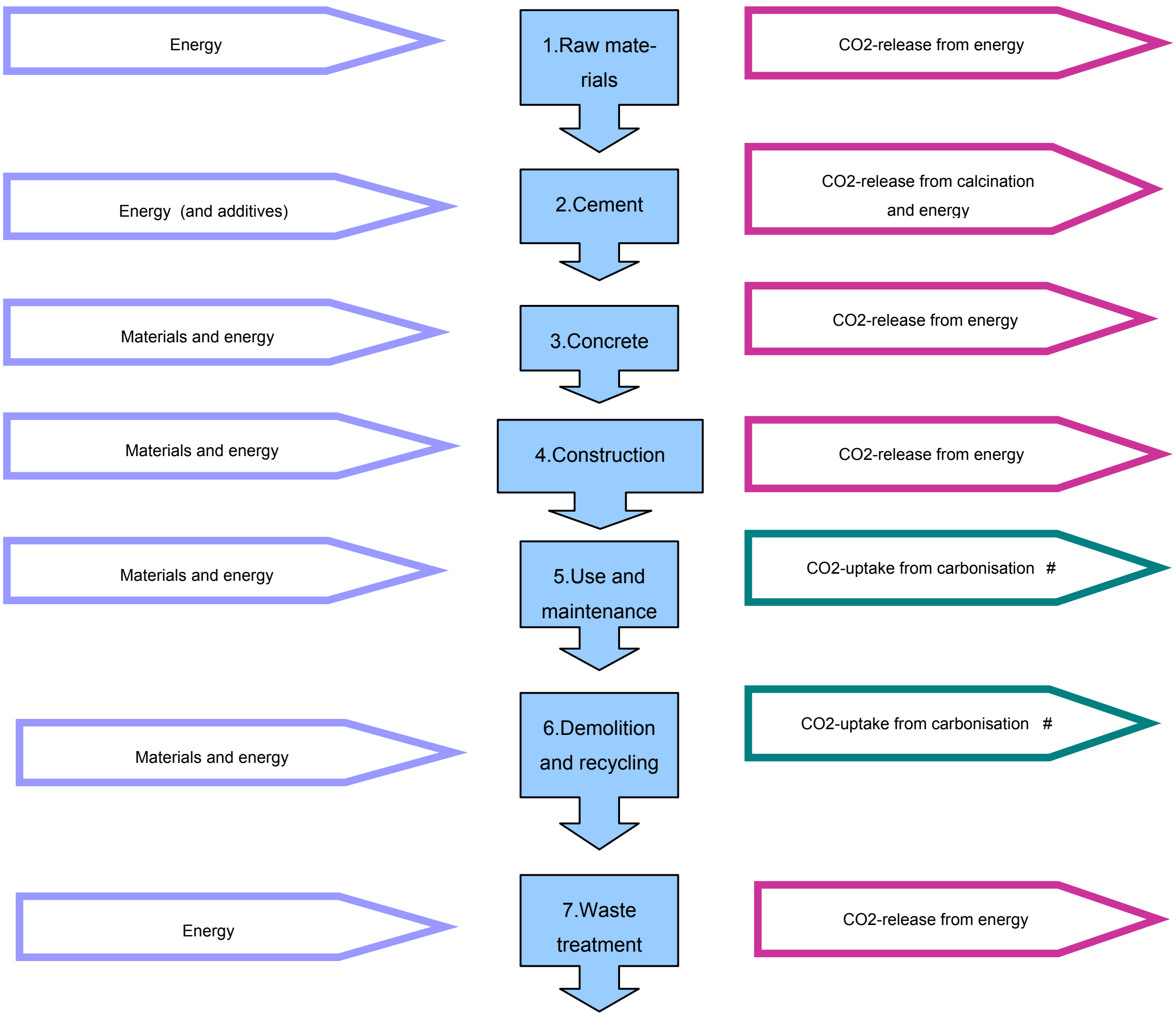


Figure 2.1: Interactions with other product systems

2.2.4 System boundaries and life cycle steps

In principle, the system includes all activities from raw materials being extracted to waste being finally landfilled. The activities are shown in Figure 2.2.



#: CO_2 will also be released when energy is used

Figure 2.2: Life cycle steps

In this definition of life cycle steps and system boundaries the scope of this assessment, - to implement carbon dioxide from carbonation, - can be seen.

In principle, the whole life cycle is included, but some limitations and omissions are made to simplify this assessment:

- Only the influences on the CO_2-balance have been included
- Heating from the use-phase is not included
- Reinforcement (steel) has not been included
- Transportation is included

Step 1	Extraction of raw materials for cement and concrete production This includes extraction of limestone, aggregates and other materials.
Step 2	Production of cement This includes production of clinker as well as grinding the clinker and substitutes as well as possible blending.
Step 3	Concrete, - **this is the functional unit** This includes mixing the cement, aggregates and other materials. Reinforcement is not included.
Step 4	Construction This included construction of the building or a concrete product. Additional materials and energy have to be included.
Step 5	Use and maintenance This includes the maintenance during the service life, consumption of materials and energy. It also includes the uptake of carbon dioxide. It does not include heating the building.
Step 6	Demolition This includes demolition of the construction, sorting the materials and crushing the concrete. It includes the consumption of energy as well as the uptake of carbon dioxide.
Step 7	Waste treatment This includes landfill of discarded concrete that not can be used for recycling.

The transport is included in the step, where the materials are transported to.

2.3 Inventory

It is always important to use reliable data, which describe the product systems in the best way, but often data for a specific process at a specific site are lacking. If data are available for a specific process, e.g. the consumption of energy for grinding clinker, then these data can be used. Besides the actual set of data it is necessary to know the uncertainty of the measurement, and also if the data are up to date and actually representing the technology used.

In many situations site specific data, as mentioned above, are now available. In some situations the site for the plant or the process is not known or can take place at many sites. In those situations average data may be more relevant to use. In such situations it is necessary to know the kind of data used for generating the average, the technology it represents as well as variations and uncertainties.

Data on uptake of carbon dioxide are based upon studies and tests carried out in the Nordic countries, and the results will be valid in this area. Results can be retrieved from the background reports. The generated data are average data, and the estimated uncertainty is considered to be in the range of 10 to 25 percent.

The calculations of the carbon dioxide uptake are essentially based on the type of cement used, concrete strength class and exposure conditions.

3. Emissions of carbon dioxide

Emission of carbon dioxide is primarily related to consumption of energy used for processes and transportation related to the clinker and cement production. This section presents some data from literature regarding each of the activities in the life cycle. These data can be used, if site-specific data are not available.

3.1 Clinker production

During the clinker production the following reaction takes place in the first part of the clinker kiln:

$CaCO_3$	→	CaO	+	CO_2
Calcium carbonate		Calcium oxide		Carbon dioxide

Pure limestone, calcium carbonate, has a mole weight of 100. Calcium oxide has a mole weight of 56 and carbon dioxide of 44. This means that when 100 kg of pure limestone is processed to calcium oxide, 56 per cent will actually be calcium oxide, while 44 per cent of the mass will be emitted as carbon dioxide.

Clinker consists of about 65 per cent calcium oxide. The rest is silicium oxide and metal oxides. When producing 100 kg of clinker, the amount of emitted carbon dioxide can thus be estimated as follows:

$$100 \text{ kg} * 0,65 * 44/56 = 51 \text{ kg}$$

The general equation for calculating the amount of emitted carbon dioxide from calcination is:

Amount of CO_2 (kg) = Amount of cement (kg) * content of clinker in cement (%) * 0.51

Some raw materials contain other sources of calcium oxide; gypsum, anhydrite, C_2S, FA, slag etc. These will not emit CO_2.

3.2 Energy consumption

The first step is to estimate the consumed quantity of energy and the type of energy. For instance, it might for a process be 10 litres of oil and 24 kWh. The emission of carbon dioxide from thermal processes is calculated in one way, the emission from electricity in another.

3.2.1 Thermal energy

If using thermal energy in the production, the emission of carbon dioxide can be calculated as shown in Table 3.1. The information given in the Table includes:

- The second column shows the resources spent for extraction, per kg heating oil is used 0.13 kg for extraction, - per Nm^3 gas is used 0.12 Nm^3. These data are given by SAEFL (1996). Data for lignite is not given, - instead data for hard coal are used.
- The third column "Energy content" is given as the lower calorific value and is based upon data from the Danish Energy Statistics, 2003.
- In the fourth column "Available energy" an efficiency factor of 0.9 for all resources is assumed.
- Carbon dioxide emitted per MJ is data from the Danish Energy Statistics, 2003. Losses are assumed not to be included.
- In the sixth column the amount of emitted carbon dioxide includes both losses by extraction and losses due to 90 per cent efficiency.
- Column 7 is simple multiplication of column 5 and 6.

Table 3.1: Energy content and emission of carbon dioxide for thermal energy production.

Energy source	Primary energy resource (kg/kg) (2)	Energy Content per kg (3)	Available energy 90% eff. per kg (4)	Carbon dioxide , gram pr MJ (5)	Carbon dioxide pr. used MJ (90% eff.) (6)	Carbon dioxide per kg used fuel (7)
Heating oil	1.13 kg	42,7 MJ	38 MJ	74.0 g	94 g/MJ	3.57 kg
Natural gas	1.12 Nm^3	39.9 MJ	36 MJ	57.2 g	71 g/MJ	2.56 kg
Coal	1.66 kg	25.2 MJ	23 MJ	95.0 g	173 g/MJ	3.98 kg
Lignite	1.66 kg	18.3 MJ	16 MJ	97.0 g	184 g/MJ	2.95 kg
Wood	1.05 kg	15.3 MJ	14 MJ	0 g	0 g/MJ	0 kg
Petrol	1.19 kg	42.8 MJ	38 MJ	72.0 g	97 g/MJ	3.69 kg
Diesel	1.09 kg	42.7 MJ	38 MJ	74.0 g	91 g/MJ	3.46 kg

If there is used 10 litres of diesel oil for a heating purpose, the amount of carbon dioxide emitted can be calculated by:

CO_2 (kg) = 10 litre * 0,84 kg/litre * 3.46 = 29.1 kg

3.2.2 Electricity

The production of electricity within the Nordic countries is very different. Therefore, when using electricity it has to be considered, where the consumption takes place geographically. Knowing the site of production is important for the estimation of carbon dioxide per kWh spent.

Table 3.2: Emitted carbon dioxide per 1 kWh consumed

	Kg CO_2 per 1 kWh
Denmark	0.753
Finland	0.352
Iceland	0
Norway	0
Sweden	0.036
European average	0.475

As can be seen from Table 3.2, electricity production in Norway and Iceland are based on hydro power. In Sweden half of the production is based on nuclear power, which does not contribute to the green house effect, and the rest is primarily hydro power. In Finland both fossil fuels as well as nuclear and hydro power are used. In Denmark the primary energy source is coal. This gives the significant differences in carbon dioxide emissions from the Nordic countries. Basic data for Table 3.2 and data for European countries are found in appendix A.

The distribution of electricity in Europe is almost connected, and export and import happen all the time. Due consideration must be given to this fact, i.e. whether or not it is more correct to use the European average rather than the value specific to the country in which the concrete product is produced.

3.3 Transportation

The basic methodology for including transportation in a life cycle assessment is to calculate the emissions from a certain amount of goods transported a certain distance by a certain mode.

This can be expressed by the following equation:

Emissions = quantity (tonnes) x distance (km) x mode (sea, road or rail) x transformation factor

For the calculation of the quantity times distance (tonnes *km), Table 3.3 can be used for calculating the CO_2-emisions from transportation.

General data for energy consumption and emissions of carbon dioxide are given in SAEFL (1996) and shown in Table 3.3.

Table 3.3: Energy consumption for transportation and emission of carbon dioxide

	Assumed efficiency	Energy resource				gram CO_2 per ton x km
		Heating oil [kg]	Diesel [kg]	Petrol [kg]	Power [kWh]	
Trans oceanic freighter	60%	0.0022				8
Inland waterways freigh-ter	70%		0.011			39
Private car, western Europe			0.012	0.051		246
Delivery van <3,5 ton	50%		0.0263	0.111		536
Lorry, 16 tons	50%		0.0635			228
Lorry, 28 tons	50%		0.0423			152
Lorry 40 tons	50%		0.0259			93
Rail, electric			0.0011		0.058	29
Rail, electric and diesel			0.0033		0.042	30

4. Uptake of carbon dioxide

When producing clinker, limestone is heated and carbon dioxide is released. In concrete, the reverse reaction takes place. Carbon dioxide is absorbed and the calcium oxide is transformed back to calcium carbonate. Tests have shown that at least 75 per cent of the calcium oxide of the cementitious part of concrete can be transformed to calcium carbonate, if enough time is given (Lagerblad, 2005). The following guidelines are based on the assumption that 75 per cent can be carbonated, equivalent to the fact that 75 per cent of the carbon dioxide released from the calcination can be chemically bound again.

The developed theory states that the amount of the concrete carbonation depends on time, strength classes, environmental classes, surface treatment and cover as well as binder types (Lagerblad 2005, Kjellsen et al 2005). The rate of carbonation and uptake of carbon dioxide depend also on the surface area of exposed concrete, and therefore the rate of carbonation during service life is slower compared to demolished material that will be reused or deposited.

For both life cycle steps, service life and secondary life, the uptake of carbon dioxide is based upon estimations of depth of carbonation, surface area and content of calcium oxide from clinker per unit of concrete. This means that knowledge about the geometry of the structure is necessary as well as the type of concrete and the exposure conditions (indoor, outdoor, surface treatment, etc.).

4.1 The use-phase

4.1.1 Depth of carbonation

The depth of carbonation $D = K * \sqrt{t}$, where
D: Depth of carbonation in mm
K: Carbonation rate factor
t : Service life in years

The constant K consists of 3 factors, where $K = k1 * k2 * k3$

The factor k1 depends on strength classes and environmental classes. The environmental classes are assumed to be typical for the Nordic climate. The factors are shown in Table 4.1.

Table 4.1: k1-values for concrete surfaces with CEMI and naked concrete surfaces (Lagerblad, 2005).

Strength	**< 15 MPa** Old concrete and some concrete products like cement bound blocks	**15-20 MPa** Old houses and some products	**25-35 MPa** Most houses today	**> 35 MPa** Most infrastructure concrete
Exposed	5 mm * (year) ^{½}	2.5 mm* (year) ^{½}	1.5 mm* (year)^{½}	1 mm* (year)^{½}
Sheltered	10 mm* (year)^{½}	6 mm * (year) ^{½}	4 mm* (year)^{½}	2.5 mm* (year)^{½}
Indoors	15 mm* (year)^{½}	9 mm* (year) ^{½}	6 mm* (year)^{½}	3.5 mm* (year)^{½}
Wet	2 mm* (year) ^{½}	1.0 mm* (year)^{½}	0.75 mm* (year)^{½}	0.5 mm* (year)^{½}
Buried	3 mm* (year) ^{½}	1.5 mm* (year)^{½}	1.0 mm* (year)^{½}	0.75 mm* (year)^{½}

The factor k2 includes corrections for surface treatment and cover, and the values are given in Table 4.2.

Table 4.2: k2 corrections for surface treatment and cover (Lagerblad, 2005)

Type	Value
Indoor house concrete	0.7
Outdoor house concrete	0.9
Infrastructure concrete	1.0

The values given in Table 4.1 are based upon CEM I. A correction factor k3 is used to include differences between CEM I and for instance CEM II. The factors for k3 are given in Table 4.3.

Table 4.3: k3, correction factors for type of supplementary cementitious material. (Lagerblad, 2005)

Type	Value	Type	Value
5-10 % silica fume	1.05	30 % fly ash	1.10
15 % limestone	1.05	20 % GBFS	1.10
30 % limestone	1.10	40 % GBFS	1.20
15 % fly ash	1.05	60 % GBFS	1.30

As an example a hollow core slab made today may be cited. The strength class is C35, and the environmental class is indoor. The k1 value for C35 and indoor is 6 mm* (years)$^{-½}$.

It is expected that the surface treatment and cover gives a k2-factor of 0.7. The slabs are made from CEM II that carbonates faster than CEM I. Because of the differences in composition a correction factor of 1.10 is included (k3).

The overall constant for the rate of carbonation will be:
K= 6 * 0.7 * 1.1 mm *(years)$^{-½}$ = 4.6 mm* (years)$^{-½}$.

The first year a layer with the depth of 4.6 mm has been carbonated. After 50 years of surface life the depth of carbonation D= 4.6 * $(50)^{½}$ = 33 mm. The hollow core slabs have a thickness of more than 200 mm, so only a part of the concrete will carbonate in 50 years of service.

4.1.2 Surface area

In order to determine the surface area that can be carbonised, the geometry of the products is important.

For many concrete products like slabs, walls, facades etc. it is characteristic that these are large flat items mainly described by the total volume and the thickness. The surface is then estimated as:

Surface (m^2) = Volume (m^3) * 2 / Thickness (m)

4.1.3 Carbonation

Given the depth of carbonation and the surface, the volume that will be carbonated can be estimated.

Next step is then to calculate the amount of carbon dioxide that will be absorbed in the given carbonated volume. This depends on the amount of cement per m^3 of concrete and the amount of clinker in the cement.

As mentioned previously it is considered that 75 % of the available calcium oxide will react with carbon dioxide. Therefore, the amount of carbon dioxide uptake can be calculated as:

CO_2 uptake = depth of carbonation (m)* surface (m^2) * 0.75 * cement (kg/m^3) * clinker in cement (%) * CaO in clinker * mole fraction (CO_2/CaO)

The equation can be written as:

CO_2 uptake = 0.383 * depth of carbonation (m)* surface (m^2) * cement (kg/m^3) * clinker in cement (%)

The depth of carbonation will change over time, the other variables have to be determined.

$$CO_2\ (t)\ uptake = 0{,}383 * surface\ (m^2) * cement\ (kg/m^3) * clin\text{ker}\ in\ cement\ (\%) * (K * \sqrt{t(years)})\ (m)$$

4.2 Demolition

When a construction is demolished, the material can be crushed (i.e. Recycled concrete aggregate, RCA) and reused. RCA will have a significant larger surface than the original structure, and the carbonation will thus take place much faster.

Estimating the uptake of carbon dioxide after demolition, the key assumptions are:

- the fraction of material processed to RCA
- the size of particles

The amount of concrete already carbonated during surface life also has to be taken into account.

4.2.1 Depth of carbonation

The principles for estimating the depth of carbonation are the same for demolition as for the use phase. The K-values are the same as shown in section 3.2.1.1. However, the environmental class should be "Buried", which gives a relative low carbonation rate factor (Table 4.1).

4.2.2 Surface

The surface area changes significantly when concrete is demolished and processed to RCA. It is proposed to use the following assumptions for particle sizes shown in Table 4.4.

Table 4.4: Particle sizes after demolition of concrete (Reference, Kjellsen et. al., 2005)

	Percentage of total demolished	Sizes (mm)	Percentage	Average Diameter (m)
Recycled material RCA	90	< 1	20	0.001
		1-10	30	0.005
		10-30	45	0.020
		>30	5	0.050
Landfilled material	10	> 100	100	0.100

The lowest k1-value given in Table 4.1 for buried environment is 0.75 mm. As this factor is higher than the radius of the smallest particle size, the smallest particles will be carbonated in less than one year for all strength classes.

If the demolished concrete can be represented by the strength class < 15 MPa, then the fraction with an average diameter of 5 mm will also be carbonated within a year. For the other fractions it will take some years, before all material is carbonated. Here the surface can be determined by using the approximation that all particles are spheres.

When the K-value is determined, the rate of carbonation is fixed. The number of years before full carbonation has to be determined for each size of particles. This can be done as illustrated below:

2 * Depth of carbonation < particle diameter equal to $2 * K * (t)^{½} = D$

$(D)^2 = 4 * K^2 * t \leftrightarrow t = (D/2K)^2$

In Table 4.5 the number of years before full carbonation is shown.

Table 4.5: Number of years before full carbonation as a function of k-values and particle size after demolition of concrete

	Number of years			
Average particle size	K = 3 mm	K = 1,5 mm	K = 1 mm	K = 0,75 mm
1	0.0	0.1	0.3	0.4
5	0.7	2.8	6.3	11.1
20	11.1	44.4	100.0	177.8
50	69.4	277.8	625.0	1111.1
100	277.8	1111.1	2500.0	4444.4

As it can be seen in Table 4.5, only the fine particles will be fully carbonated within a reasonable time frame.

It is suggested to use a period of 100 years for service life and secondary life. Therefore, if the service life is assumed to be 70 years, the secondary life is advised to be 30 years. For products, where a shorter service life is expected, the included secondary life time will be longer (e.g. roof tiles, where service life is 50 years, then 50 years of secondary life is included).

4.2.3 Carbonation

The amount of carbon dioxide uptake can be calculated the same way as for the use phase. The calculation of surface and volume is a little more complicated, but otherwise it is the same. The volume available for carbonation after demolition is the total volume of concrete subtracted the volume already carbonated during service life. The volume available for carbonation after demolition therefore has to be reduced by the fraction

F = (volume total – volume carbonated during service life) / total volume

The equation for CO_2-uptake after demolition can therefore be expressed as:

$$CO_2\ (t)\ uptake = 0{,}383 * surface\ (m^2) * cement\ (kg/m^3) * clinker\ in\ cement\ (\%) * F * (K * \sqrt{t(years)})\ (m)$$

5. The carbon dioxide balance

The carbon dioxide balance can be calculated by using a simple tool, - an excel sheet. Given a set of assumptions the amount of emitted and absorbed carbon dioxide for the whole life cycle and a construction can be calculated. It can be used for identifying the most important activities regarding carbon dioxide or for comparing two products with the same service and quality.

During the development of the tool, it was the goal to construct an excel sheet in such a way that it is almost self explanatory and easy to use for most people in the industry. The tool "Balance of carbon dioxide" is developed on the basis of the findings presented in chapter 2 to 4 in this report.

5.1 Using the tool

The tool is designed, so it includes a front page with brief instructions, 14 pages of calculations where changes may be introduced, and 2 pages with the results. All pages are standardised (A4), so that printing is easily done for documentation.

When using the tool, some cells will appear coloured.

(blue)	Blue means explanatory text
(yellow)	Yellow means that the content of these cells has to be considered and most likely changed
(green)	Green means calculated figures that might be important

In many situations a choice has to be made. It may be choosing a geographical location or choosing a strength class. In these situations the options are listed, and a "1" has to be stated for the chosen option and "0" for the rest.

5.2 Defining the product

The tool has been made easy to use by including a set of default values for a number of parameters, for instance transport distances. The default values may be changed if needed. But there are some essential data that must be stated. In the data sheet labelled "1.Product definition" data for the functional unit as well as the composition of cement and concrete have to be stated.

The minimum amount of data for the functional unit is:
- Description: e.g. concrete slab + quality (strength class, exposure class)
- The weight of the product
- The service life of the product

There is room for including a qualitative short description for documentation.

The composition of the concrete is necessary. Here the most important information is the amount of cement. Data for the composition of the cement have to be given. The essential parameter here is obviously the amount of clinker. As for concrete, other materials may be included. It is assumed that the amount of calcium oxide in the clinker is 65 per cent. This assumption may be changed to another number.

In the calculations it is possible to include consumed energy for extraction of aggregates and transport of different types of materials. To include this, the amount of each type of material has to be specified.

5.3 General default values

In the following the basic default data for calculating CO_2-emission and uptake for the life cycle of a concrete functional unit are given. The numbers used in the following subtitles are referring to the numbers of the actual data sheet in the tool.

Sheet no. 3: Raw materials
Extraction of raw materials, primarily limestone is estimated to consume 1 kg diesel oil per ton. This is given as default.

Extraction of aggregates. In the EU-project ECO-SERVE, Task 2 (1), it is stated that the energy consumption may vary between 0,029 to 0,068 MJ/kg. This is equivalent to 0,75 - 1,75 kg diesel oil per ton. Therefore the default value 1 kg per ton is used for coarse aggregates and 1,5 kg per ton is used for fine aggregates.

Sheet no. 4: Transport of raw materials
Transport of raw materials from site of limestone source to processing plant is assumed to be 10 km by a large truck.

It is possible to include transport of other materials to production of cement, for instance fly ash or slag for blended cement.

Sheet no. 5: Production of cement
Energy for heating / burning clinker, for grinding and mixing is given here. The data are based on data from Aalborg Portland and may be changed. Data for Aalborg Portland are based on their Annual Environmental Report ("miljøredegørelse, 2003”) (8).

Sheet no. 6: Transport of cement
Cement is transported to the site for production of concrete. Together with cement, also aggregates and other materials have to be transported. For each type of material the distance of transport has to be stated. Aggregates are normally extracted locally, while cement and fly ash/slag have to be transported a longer distance.

Sheet no. 7: Mixing concrete
Energy used for mixing concrete may vary. As default value the consumption of 1 kWh and 1 litre diesel per tonne material is used.

Sheet no. 8: Transport of concrete
Here a short distance of transportation is assumed equivalent to 25 kilometres.

Sheet no. 9: Construction
In the EU-project "Tescop" (5), data on energy consumption during construction have been about 2 -4 kWh per ton or 0,2 - 0,4 kg diesel oil. As default value 0.3 kg diesel oil is used.

Sheet no. 10: Use and maintenance
This part comes in two sections, one for energy consumption for use and maintenance and a section for uptake of carbon dioxide during service life.

As default value no energy consumption is included for use and maintenance. If energy has to be included, state the total amount of energy used during the whole period of surface life. Uptake of carbon dioxide is included in the calculation of the CO_2-balance. If it has to be excluded, state a "0" for the surface area in sheet 10 cell E54. If you want to include uptake of carbon dioxide during service life, the following parameters have to be considered.

- Estimation of surface area can be changed.
- Strength class and environmental class have to be defined. Default is strength class 25-35 MPa and the environmental class "Sheltered".
- Also a factor for surface treatment and binder type has to be considered.

Sheet no. 11: Demolition and recycling
This part comes in two sections, one for energy consumption for demolition and a section for uptake of carbon dioxide during use of recycled material.

The amount of consumed energy for demolition is assumed to be 0.75 litre diesel oil and for grinding 0,25 litre diesel oil and 1 kWh electricity.

Uptake of carbon dioxide is included in the calculation of the CO_2-balance. If it has to be excluded, state a “0” for the surface area in sheet 11 cell F57. The strength class has to be defined. Environmental class is assumed to be “buried”. The default value for strength class is 25-35 MPa.

Sheet no. 12: Transportation
Here the distance of transportation is assumed to be 25 kilometres for both landfill and recycling.

5.4 The tool

The following is a presentation of the tool used for calculating the inventory balance of carbon dioxide for a construction.

The front page looks as illustrated in Figure 5.1.

Balance of carbon dioxide

emissions and up-take during the concrete life cycle

In this spread sheet the balance of carbon dioxide can be calculated for a concrete item in its life cycle.

The spread sheet consists of several sheets, -an introduction and some pages, where the activities in the life cycle are described.
Default values are given and can be changed by the user. Background data should not be changed.

The pages included in this folder are:
1. Definition of the product
2. Definition of the life cycle steps
3. Extraction of raw materials
4. Transport from extraction site to cement plant
5. Production of cement
6. Transport of materials to plant for concrete
7. Production of concrete
8. Transport from concrete plant to construction site
9. Construction
10. Use and maintenance
11. Demolition and recycling
12. Transport of demolished materials

Figure 5.1: Tool for balance of CO_2, front page

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1. Product definition

Define the functional unit, first by a breif description, then by some exact data.
The function of the product is ……..

Functional unit:
The product is a edge beam of a highway concrete bridge

Service life time	70	years
Weight	0,50	tons per unit
Quality		
Other properties		

Composition of the concrete

Components	Per m3 (kg)	Per unit (kg)
Cement	238	52,6
Fly ash	135	29,8
Fine aggregates	579	127,9
Coarse aggregates	1160	256,3
Others	27	6,0
		0,0
		0,0
Water	133	29,4
In total	2272	502,0

Materials for production of 1 tonne of cement

Components [kg per ton]	Portland cement	Type 1	Type 2	Type 3	Actual	Per unit
Clinker	950				950	49,96
Fly ash	0				0	0,00
Gypsum	50				50	2,63
Blast funce slag					0	0,00
						0,00
In total	1000				1000	52,59

Materials for production of 1 tonne of clinker
Pecent of calcium oxide in clinker 65

The clinker in the concrete above consists of

Calcium oxide (kg)	32,5
Others (kg)	17,5

Raw materials

Limestone, pure (kg)	58,0
Others (kg)	17,5
Gypsum	2,6
Fly ash	0,00
Blast funce slag	0,00

Figure 5.2: Tool for balance of CO_2, Product definition

An example of how a geographical location can be chosen is illustrated in Figure 5.3. As can be seen a mix of electricity corresponding to a European average is chosen by putting a “1” in the row “EU-25 average” and “0” in the rest.

|

3. Extraction of raw materials

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In this section the emissions of carbon dioxide from the use of energy for extraction of the raw materials are calculated.

The emissions of carbon dioxide from consumption of electricity depend on the basis resources used, and this varies through out Europe. Therefore the location of the extraction has to be defined.
As default value an European avarage is used, - this can be used if no specific information is available.

A: Extraction of raw materials for cement production

Electricity	kg CO_2	Component					
Location	per kWh	Others (kg	Fly ash	Gypsum	Blast funce s	0	Limestone, pure (kg)
Denmark	0,753	1	1	1	1	1	1
Finland	0,352	0	0	0	0	0	0
Iceland	0	0	0	0	0	0	0
Norway	0	0	0	0	0	0	0
Sweden	0,036	0	0	0	0	0	0
Nordic avarage	0,147	0	0	0	0	0	0
EU-25 avarage	0,475	0	0	0	0	0	0

Figure 5.3: Tool for balance of CO_2, Calculation of emissions from consumption of electricity

Below in Figure 5.4 it is shown, how the fuels for clinker production and other activities related to production of cement are calculated. The amount consumed per ton cement produced has to be stated.

The emission of carbon dioxide from the processes based on energy consumption of fossil fuels and from calcination is calculated.

Amount of cement per unit (kg)	52,59
Calcium oxide (kg)	32,47
Amount of clinker per unit (kg)	49,96

	Hard coal [kg/ton]	Lignite [kg/ton]	Oil [kg /ton]	Gas [m3/ton]	Electricity [kwh/ton]	Renew-ables	Others	CO_2 (kg) per unit
kg CO2 per kg or m3	3,98	2,95	3,59	2,29	0,475	0	0	
Clinker production	200		35	9,5	0	0	0	47,130
Grinding			0	0	0	0	0	0,000
Blending			0	0	0	0	0	0,000
Others			0	0	0	0	0	0,000
In total								47,130

Total emitted CO_2 kg per unit	
Calcination	25,523
Other processes	47,130
Step 5, sum	72,653

Figure 5.4: Tool for balance of CO_2, Calculation of emissions from consumption of energy resources

How emissions from transportation are calculated is shown in Figure 5.5.

CO_2 per ton x km [kg] Components	kg per unit	Distance Total km	Truck 16 tons 0,228	Truck 40 tons 0,093	Rail Electric 0,029	Rail E+Diesel 0,03	Ship oceanic 0,008	Ship inland 0,039	CO_2 per unit (kg)
Cement	52,6	100	0	100	0	0	0	0	0,489
Fly ash	29,8	50	50	0	0	0	0	0	0,340
Fine aggregates	127,9	10	0	10	0	0	0	0	0,119
Coarse aggregates	256,3	10	0	10	0	0	0	0	0,238
Others	6,0	0	1	0	0	0	0	0	0,001
0	0,0	0	1	0	0	0	0	0	0,000
0	0,0	0	1	0	0	0	0	0	0,000
Water	29,4	0	1	0	0	0	0	0	0,007
Total									1,194

Figure 5.5: Tool for balance of CO_2, Calculation of emissions from transportation

Carbon dioxide uptake
Estimation of the uptake of carbon dioxide during use is based on the rate of carbonation, the number of years and the surface of the unit.
The time is given by the service life. The surface can be calculated or given in m^2
The rate of carbonation depend on the type of concrete, environmental exposure and other parameters, - these can be determined in the following procedure:

Service life (years) 70
Unit weight (kg) 502

Surface of the construction: Can be calculated as the volume times two divided by the thickness or given as an actual figure.

Thickness of the unit (m) 0,2

Area (m^2) 2,21
Change the surface area here if necessary 2,21

Type of concrete, strength and environmental class

Choose the category by putting a "1" in the right cell	Exposed	Sheltered	Indoors	Wet	Buried
Old concrete and some concrete products like cement bo	0	0	0	0	0
15- 20 MPa, Old houses and some products	0	0	0	0	0
25-35 MPa, Most houses today	0	0	0	0	0
> 35 MPa, Most infrastructure concrete	1	0	0	0	0

Continues

Figure 5.6: Tool for balance of CO_2, basic parameters for uptake during service life

Correction for surface treatment and cover, -
Choose the category by putting a "1" in the right cell

Indoor house concrete	0
Outdoor house concrete	0
Infra structure concrete	1
K2	1

Correction factors for types of supplementary material, -
-Choose the category by putting a "1" in the right cell

Type	
5-10 % silica fume	0
15 % limestone	0
30% limestone	0
15% fly ash	0
30% fly ash	1
20 % GBFS	0
40% GBFS	0
60 % GBFS	0
K3	1,1

K (mm) 1,1

Depth of carbonation is :	D (mm)	9	D(m)	0,009
Volume carbonated	V (m3)	0,020339	Max Volume (m3)	0,220951
Amount of CO2-uptake (kg)	1,761			

Figure 5.7: Tool for balance of CO_2, calculations for uptake during service life

When a construction is demolished, a part of the material will be reused as aggregates in other constructions.

The carbon dioxide balance is determined by the use of energy for demolition and uptake in the secondary life.

Fraction of recycling (%) 90

Energy

Electricity Location	kg CO_2 per kWh	
Denmark	0,753	0
Finland	0,352	0
Iceland	0	0
Norway	0	0
Sweden	0,036	0
Nordic average	0,147	0
EU-25 average	0,475	1

Demolition includes the whole unit equal to 502 kg
Grinding includes the part for recycling 451,8 kg

	Oil [kg /ton]	Gas [m^3/ton]	Electricity [kwh/ton]	Renew-ables	Others	CO_2 (kg) per unit
kg CO_2 per kg or m^3	3,59	2,29	0,475	0	0	
Demolition	2	0	0	0	0	3,604
Grinding	2		1	0	0	3,459
Total						7,063

The following is assumed for the particle sizes of the demolished and ground concrete

	percent	Sizes (mm	Av. D. (m)	percentage
Recycled Material	90	<1	0,001	20
		1-10	0,005	30
		10-30	0,020	45
		>30	0,050	5
Landfilled	10	> 100	0,100	100

0,75

The K-value to be used is for buried environment and is only determined by the strength class

< 15 Mpa	0
15-20 Mpa	0
25-35 mPA	0
>35 Mpa	1
K=	0,75

Lifespan for carbonation of demolished material(years) 30

Depth of carbonation (mm) 4,1

All perticles with a diameter of 8,2 mm will be fully carbonated.

Figure 5.8: Tool for balance of CO_2, basic parameters for uptake during secondary life

The results from the uptake of carbon dioxide, when the material is crushed, and when part of it is reused, are shown in Figure 5.9.

Calculation of carbonated volume							
Total volume of unit (m^3)			0,221	Depth of carbonation (m)			0,0041
Carbonated volume during service life			0,020				
Volume of particles < 1 mm (m^3)			0,040				
Volume of particles 1 - 10 mm (m^3)			0,060				
Volume of particles 10 - 30 mm (m^3)			0,089				
Volume of particles > 30 mm (m^3)			0,010				
Material not recycled, diameter of particles D=100			0,022				
Carbonated volume							
Particles <1 mm	R1=	0,0005		R2=	-0,003607919	Vol=	0,040
Particles 1-10 mm	R1=	0,0025		R2=	-0,001607919	Vol=	0,060
Particles 10-30 mm	R1=	0,01		R2=	0,005892081	Vol=	0,071
Particles >30 mm	R1=	0,025		R2=	0,020892081	Vol=	0,004
Particles > 100 mm	R1=	0,05		R2=	0,045892081	Vol=	0,005
Carbonated volume							0,180
Carbonated during service life							0,020
Uptake of carbondioxide (kg) =		14,128					

Figure 5.9: Tool for balance of CO_2, results for uptake during secondary life

The overall results can be presented in different ways. Data are given in a table, and these data can be further transformed for specific purposes.

In the following all the emissions and uptake of carbon dioxide from the life cycle are presented.
Assumptions, omissions and specific details can be seen at the sheet for the specific life cycle phase.

For a contruction of 0,50 Tonnes per unit the following CO_2-ballance has been estimated.

	kg CO_2 per unit	Acc kg CO_2 per unit
3. Extraction of raw materials	1,685	1,685
4. Transport from extraction site to cement plant	0,229	1,913
5. Production of cement	72,653	74,566
6. Transport of materials to plant for concrete	1,194	75,760
7. Production of concrete	9,011	84,771
8. Transport from concrete plant to construction site	1,167	85,938
9. Construction	0,901	86,840
10. Use and maintenance	0,000	86,840
10 A Uptake of CO_2 during service life	-1,761	85,079
11. Demolition and recycling	7,063	92,142
11 A. Uptake of CO_2 after demolition	-14,128	78,014
12. Transport of demolished materials	1,337	79,350
In total	79,350	

Emission from calcination	25,523	kg CO_2 per unit
Uptake from carbonation	15,889	kg CO_2 per unit
Max theoretical uptake (75% of CaO)	19,126	kg CO_2 per unit

Figure 5.10: Tool for balance of CO_2 - table with total results

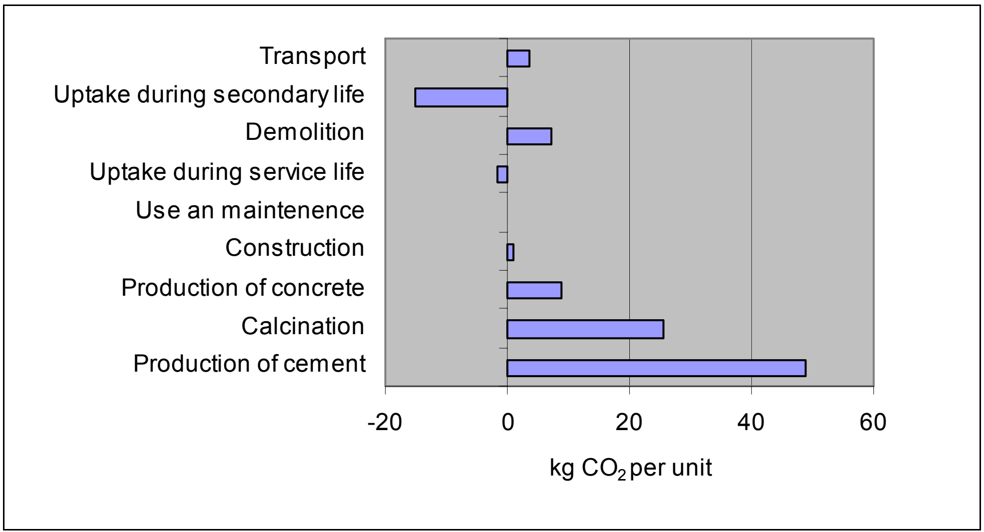

Figure 5.11: Example of presentation of results

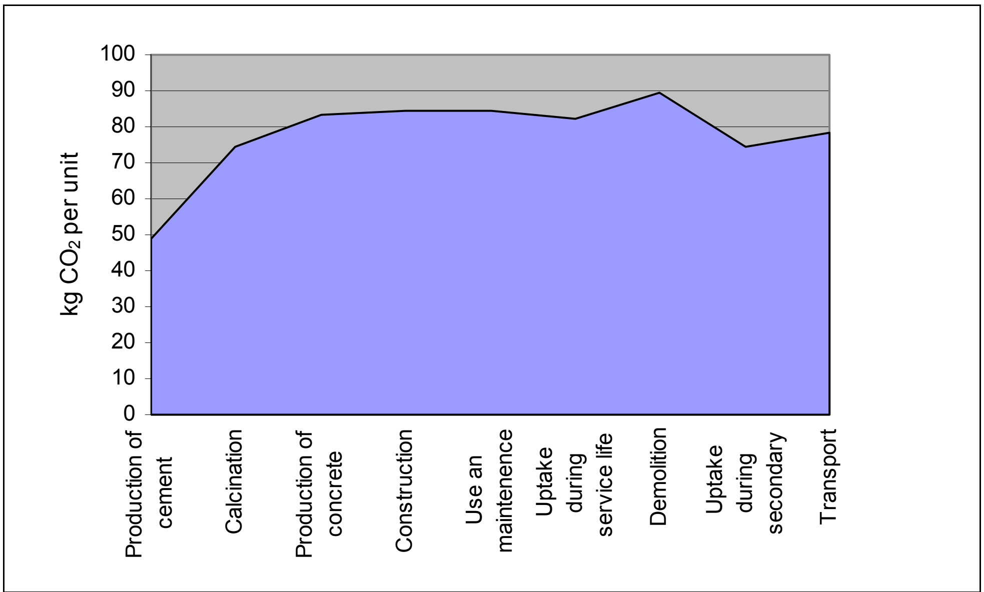

Figure 5.12: Example of presentation of results

6. Examples

Two different and widely used products have been chosen to illustrate the effect of CO_2-uptake.

The examples chosen are:
- An edge beam as a part of a highway bridge construction
- A typical roof tile

The composition of the concrete, the service life and the strength and environmental classes are different in the examples and illustrate various scenarios for the uptake of carbon dioxide.

6.1 Example 1: Edge beam – Highway bridge

6.1.1 The product and assumptions

This example includes an edge beam of 502 kg. The service life is 70 years, and it is assumed that the concrete has a strength class of "more than 35 MPa" and that the environmental class is outdoor "Exposed".

The composition of the concrete is as shown in Table 6.1.

Table 6.1: Composition of concrete in example 1

Components	Per m^3 (kg)	Per unit (kg)
Cement	238	52.6
Fly ash	135	29.8
Fine aggregates	579	127.9
Coarse aggregates	1160	256.3
Others	27	6.0
Water	133	29.4
In total	2272	502.0

It is assumed that the cement consists of 95% Portland clinker and 5% of other materials. It is also assumed that 65% of the clinker is calcium oxide.

After demolition it is assumed that 90% of the material is reused as recycled concrete aggregates (RCA).

The detailed calculations and assumptions are included in appendix B.

6.1.2 Results

The clinker part of the cement represents 32,5 kg CaO per unit. The consideration in this project (Lagerblad, 2005) is that 75% of this amount can be carbonated, equal to 24.4 kg. This is equivalent to a carbon dioxide emission of 25.5 kg from calcinations and a maximal carbon dioxide uptake from carbonation of 19.2 kg.

The calculations show that the beam has an area of 2.21 m^2 and a thickness of 200 mm. The depth of carbonation is 9 mm based on a carbonation rate factor (K) of 1.1. The total volume of the beam is 0.221 m^3, and the carbonated volume is 0.020 m^3 equal to a carbonation of 9%.

After demolition and crushing the uptake is based upon a carbonation depth of 4.1 mm and a k-value of 0.75. During secondary life most of the material will be carbonated, - 0,180 m^3 equal to 81%. The uptake of carbon dioxide after demolition and crushing is therefore 81% - 9% = 72%.

The calculations show that overall 81% of the potential amount of CO_2-uptake has been absorbed within 100 years.

The results from the calculations of the balance for the whole life cycle are shown in Table 6.2.

Table 6.2: Balance of carbon dioxide in example 1

	kg CO_2 per unit	Acc kg CO_2 per unit
3. Extraction of raw materials	1,685	1,685
4. Transport from extraction site to cement plant	0,229	1,913
5. Production of cement	72,653	74,566
6. Transport of materials to plant for concrete	1,194	75,760
7. Production of concrete	9,011	84,771
8. Transport from concrete plant to construction site	1,167	85,938
9. Construction	0,901	86,840
10. Use and maintenance	0,000	86,840
10 A Uptake of CO_2 during service life	-1,761	85,079
11. Demolition and recycling	7,063	92,142
11 A. Uptake of CO_2 after demolition	-14,128	78,014
12. Transport of demolished materials	1,337	79,350
In total	79,350	

The results are also illustrated in Figure 6.1.

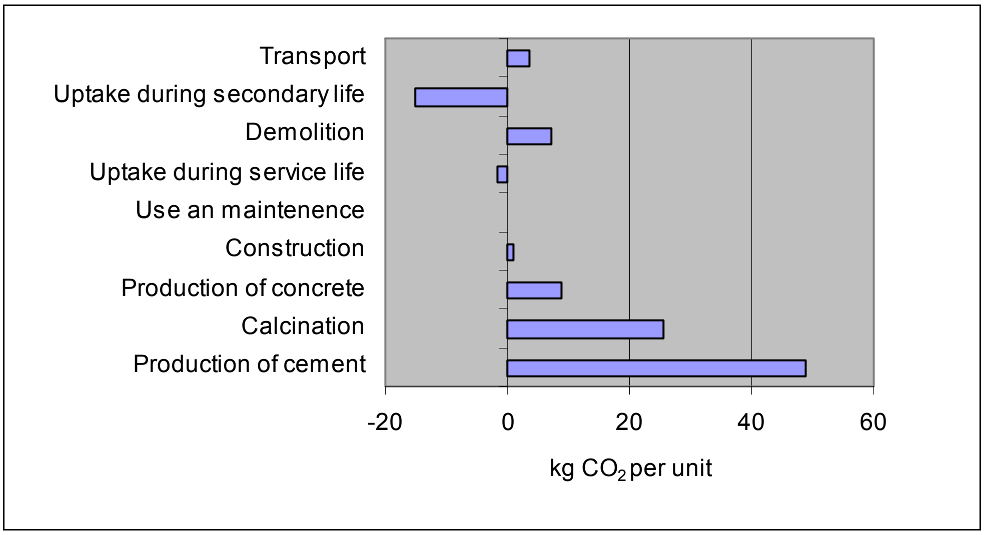

Figure 6.1: Balance of carbon dioxide for example 1.

6.2 Example 2: Roof tile

6.2.1 The product and assumptions

This example is 1 m^2 of typical roof tile with a weight of 42 kg. The service life is 50 years, and it is assumed that the concrete has a strength class of "> 35 MPa", and that the environmental class is outdoor "Exposed".

The composition of the concrete and the cement are shown in Table 6.3 and Table 6.4, respectively.

Table 6.3: Composition of concrete in example 2

Components	Per m3 (kg)	Per unit (kg)
Cement	480	8.4
Fine aggregates	1760	30.7
Others	2	0.0
Water	166	2.9
In total	2408	42.0

Table 6.4: Composition of cement in example 2

Components [kg per ton]	Per ton	Per unit
Clinker	917	7.68
Limestone	40	0.33
Gypsum	37	0.31
Iron sulfate	6	0.05
In total	1000	8.37

After demolition it is assumed that 90% of the material is reused as recycled concrete aggregates (RCA).

The detailed calculations and assumptions are included in appendix C.

6.2.2 Results

The clinker part of the cement contains 5,0 kg CaO per unit. It is assumed that 75 per cent of this amount can be carbonated, equals 3.75 kg. The clinker content is equivalent to a carbon dioxide emission of 3.9 kg from calcination and a maximum CO_2 uptake from carbonation of 2.9 kg.

It is assumed that the roof tile has a surface area of 2 m^2. With a unit mass of 42 kg , this equals a volume of 0.017 m^3. The thickness of the tiles will be 17 mm.

In this case the carbonation rate constant was measured to be 0.37 resulting in a carbonation depth of 3 mm after 50 years (6).

The volume of the tile carbonated after 50 years is 0.005 or 30 % of the total volume.

After demolition and crushing the CO_2 uptake is estimated based on a K-factor 0.37, meaning that all crushed particles up to 5.2 mm will be fully carbonated in 50 years. During secondary life a volume of 0,08 m^3 will carbonate corresponding to 42 %. However, 30 % was already carbonated so all together 72 % of the roof tile will be carbonated in 100 years.

The results from the calculations of the balance for the whole life cycle are shown in Table 6.5.

Table 6.5: Balance of carbon dioxide in example 2

	kg CO_2 per unit	Acc kg CO_2 per unit
3. Extraction of raw materials	0,178	0,178
4. Transport from extraction site to cement plant	0,038	0,216
5. Production of cement	6,077	6,293
6. Transport of materials to plant for concrete	0,107	6,400
7. Production of concrete	0,754	7,154
8. Transport from concrete plant to construction site	0,391	7,544
9. Construction	0,075	7,620
10. Use and maintenance	0,000	7,620
10 A Uptake of CO_2 during service life	-0,882	6,738
11. Demolition and recycling	0,591	7,329
11 A. Uptake of CO_2 after demolition	-1,480	5,848
12. Transport of demolished materials	0,112	5,960
In total	5,960	

The results are also illustrated in Figure 6.2.

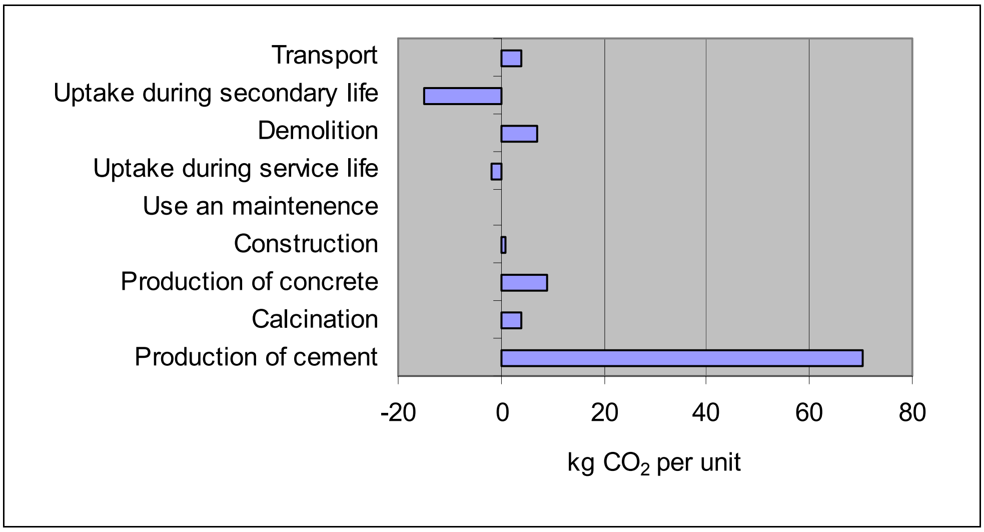

Figure 6.2: Balance of carbon dioxide in example 2

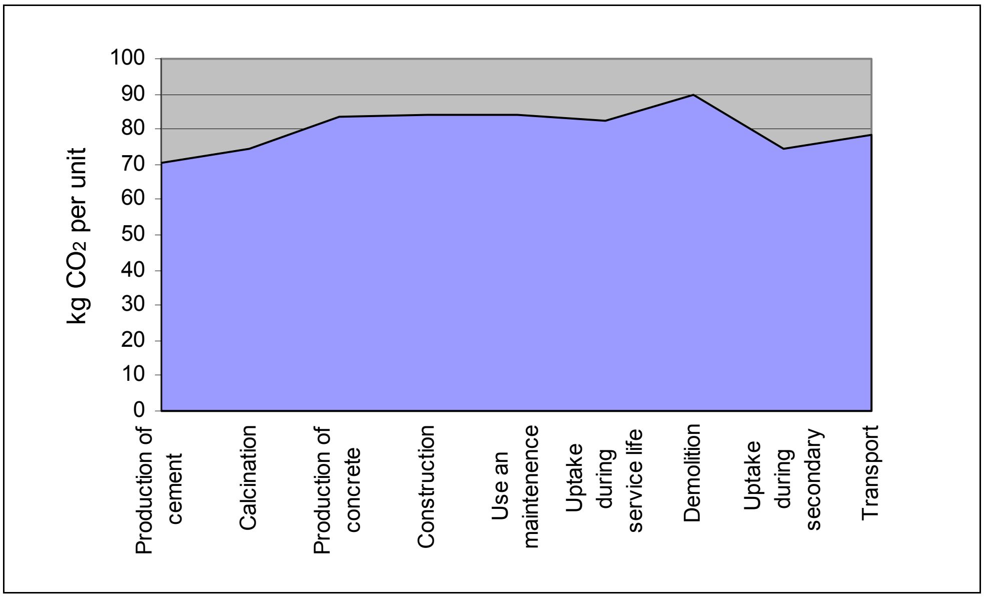

Figure 6.3: Balance of carbon dioxide in example 2, accumulated

7. References

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Appendix A

CO_2 emissions from production of electricity

The relevant data for electricity in this context are those, which state the type and the amount of each energy resource used to produce 1 kWh for the consumer. From this the amount of CO_2 emitted by using 1 kWh can be calculated.

Such data are normally not included in ordinary statistics. The data generated by ETH Zürich, Institut für Verfahrens- und Kältetechnik (IVUK) are often used in LCA's. In Table A.1 the data (SAEFL, 1996) for emitted carbon dioxide per 1 kWh from different energy sources are presented.

Table A.1: Energy consumed and CO_2-emissions for producing 1 kWh (3,6 MJ)

	Raw material	Energy	CO_2-emitted
Oil	0.275 kg	9.68 MJ	0.88 kg
Gas	0.241 Nm3	6.93 MJ	0.77 kg
Nuclear energy	0.029 gram	9.64 MJ	0 kg
Hard Coal	0.613 kg	9.1 MJ	0.98 kg
Brown Coal	1.48 kg	10.9 MJ	1.35 kg
Hydro	4.7 m^3	1.1 MJ	0 kg

At the homepage of Energy Information Administration data regarding production of electricity are given, - International Energy Annual 2002 at the web-site http://www.eia.doe.gov/pub/international/iea2002/table63.xls. Here data for the annual production of 2002 for a number of countries are given and divided in the types of resources: Thermal, hydroelectric, nuclear and renewables.

It has been tried to divide the data for thermal energy, which includes oil, gas and coal into the three types of resources. Energy data for the EU-15 resources has been found for 1999 in the article "Diversity of fuels used to generate electricity in the UK, EU and other major electricity producing countries". Here is given data for percentage of coal, gas and oil. For the other countries data has been retrieved at the homepage http://www.eva.ac.at/enercee/ .

The data for electricity production is presented in Table A.2.

Table A.2: Selected data regarding electricity from World Net Electricity Generation by Type, 2001

Billion kWh	Conventional			Renew-ables	Total	Coal, oil and gas	Hydro	Nuclear	Solar, Wind and Waste
Region/ Country	Thermal	Hydro electric	Nuclear						
						in percentage			
Austria	17,33	41,42	0,00	2,05	60,79	29	68	0	3
Belgium	28,40	0,44	44,03	1,54	74,40	38	1	59	2
Bosnia and Herzegovina	5,34	4,69	0,00	0,00	10,03	53	47	0	0
Croatia	5,26	6,52	0,00	0,001	11,78	45	55	0	0
Denmark	**29,29**	**0,03**	**0,00**	**6,09**	**35,41**	**83**	**0**	**0**	**17**
Finland	**27,93**	**13,07**	**21,66**	**8,32**	**70,98**	**39**	**18**	**31**	**12**
France	43,95	73,71	400,90	3,54	522,10	8	14	77	1
Germany	342,39	20,25	162,64	22,63	547,90	62	4	30	4
Greece	47,04	2,08	0,00	0,89	50,01	94	4	0	2
Iceland	**0,004**	**6,51**	**0,00**	**1,38**	**7,89**	**0**	**82**	**0**	**17**
Ireland	22,19	0,59	0,00	0,41	23,19	96	3	0	2
Italy	203,01	46,34	0,00	8,66	258,01	79	18	0	3
Luxembourg	0,26	0,13	0,00	0,08	0,48	55	28	0	17
Macedonia, TFYR	5,39	0,62	0,00	0,00	6,01	87	13	0	0
Netherlands	80,01	0,12	3,78	4,31	88,21	91	0	4	5
Norway	**0,50**	**119,21**	**0,00**	**0,31**	**120,03**	**0**	**99**	**0**	**0**
Portugal	28,36	13,89	0,00	1,86	44,12	64	31	0	4
Slovenia	4,82	3,74	5,04	0,07	13,66	35	27	37	0
Spain	112,54	40,61	60,52	9,77	223,45	50	18	27	4
Sweden	**6,02**	**78,35**	**65,75**	**3,80**	**153,92**	**4**	**51**	**43**	**2**
Switzerland	0,86	40,90	25,47	1,44	68,66	1	60	37	2
United Kingdom	266,28	4,02	85,61	5,74	361,64	74	1	24	2
Yugoslavia (Serbia and Montenegro)	19,00	11,49	0,00	0,00	30,48	61	39	0	0
Czech Republic	53,32	2,03	14,01	0,68	70,04	75	14	11	1
Estonia	7,96	0,01	0,00	0,01	7,97	100	0	0	0
Hungary	20,66	0,18	13,42	0,12	34,38	61	0	39	0
Latvia	1,36	2,81	0,00	0,00	4,16	33	67	0	0
Lithuania	2,43	0,69	11,36	0,00	14,49	17	5	78	0
Poland	132,18	2,30	0,00	0,74	135,22	94	6	0	1
Slovakia	9,04	4,88	16,25	0,00	30,16	30	16	54	0
Romania	31,49	14,77	5,04	0,00	51,30	61	29	10	0

Renewables include: Geothermal, Solar, Wind, and Wood and Waste

By combining the data shown in Table A.1 and A.2 the average amount of carbon dioxide emitted per consumed unit of electricity in the different countries can be estimated. This is presented in Table A.3 for the Nordic countries and in Figure A.1 for the European countries.

Table A.3: Emitted carbon dioxide per 1 kWh consumed

	Kg CO_2 per 1 kWh
Denmark	0.753
Finland	0.352
Iceland	0
Norway	0
Sweden	0.036

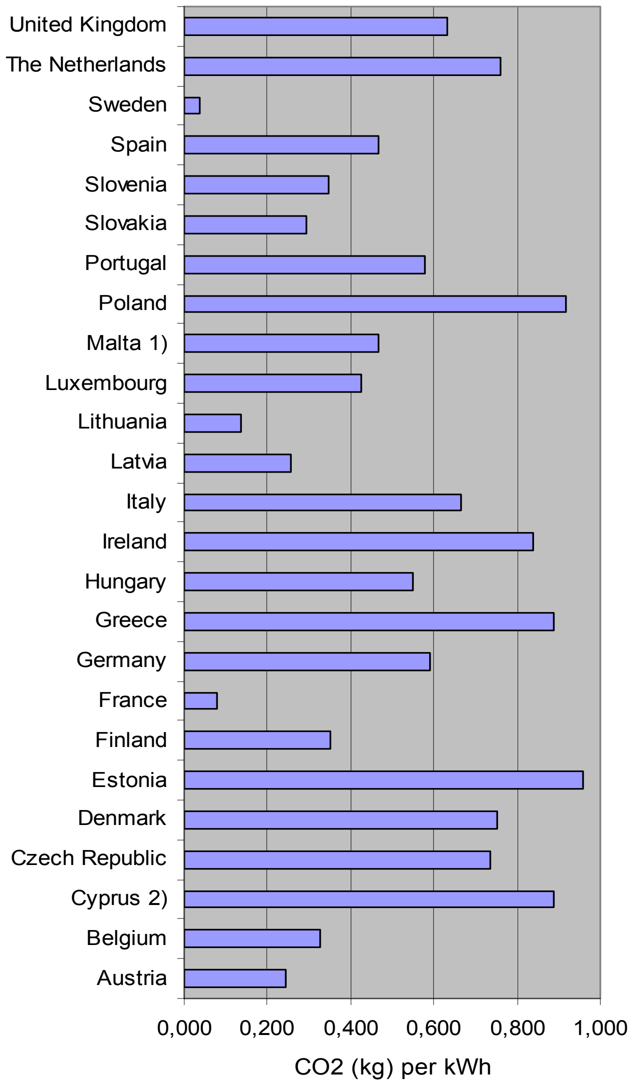

Figure A.1: Average emission of carbon dioxide per 1 kWh used

Appendix B

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Balance of carbon dioxide

emissions and up-take during the concrete life cycle

In this spread sheet the balance of carbon dioxide can be calculated for a concrete item in its life cycle.

The spread sheet consists of several sheets, -an introduction and some pages, where the activities in the life cycle are described.
Default values are given and can be changed by the user. Background data should not be changed.

The pages included in this folder are:
1. Definition of the product
2. Definition of the life cycle steps
3. Extraction of raw materials
4. Transport from extraction site to cement plant
5. Production of cement
6. Transport of materials to plant for concrete
7. Production of concrete
8. Transport from concrete plant to construction site
9. Construction
10. Use and maintenance
11. Demolition and recycling
12. Transport of demolished materials

Limitations and omissions
Interactions with other systems - has to be determined
Reinforcement has not been included
Heating from the use-phase (no. 10) has not been included

Use of the spread sheet:
The spread sheet has been designed with data for 10 m2 of pavers as an example.
Work trough the 13 pages and consider adequate changes with respect to the actual product.
Data that may be changed are marked with a remark.

All the sheets are designed so that they can easily can be printed for documentation.

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1. Product definition

Define the functional unit, first by a breif description, then by some exact data.
The function of the product is ……..

Functional unit:
The product is a edge beam of a highway concrete bridge

Service life time	70	years
Weight	0,50	tons per unit
Quality		
Other properties		

Composition of the concrete

Components	Per m3 (kg)	Per unit (kg)
Cement	238	52,6
Fly ash	135	29,8
Fine aggregates	579	127,9
Coarse aggregates	1160	256,3
Others	27	6,0
		0,0
		0,0
Water	133	29,4
In total	2272	502,0

Materials for production of 1 tonne of cement

Components [kg per ton]	Portland cement	Type 1	Type 2	Type 3	Actual	Per unit
Clinker	950				950	49,96
Fly ash	0				0	0,00
Gypsum	50				50	2,63
Blast funce slag					0	0,00
						0,00
In total	1000				1000	52,59

Materials for production of 1 tonne of clinker	
Pecent of calcium oxide in clinker	65

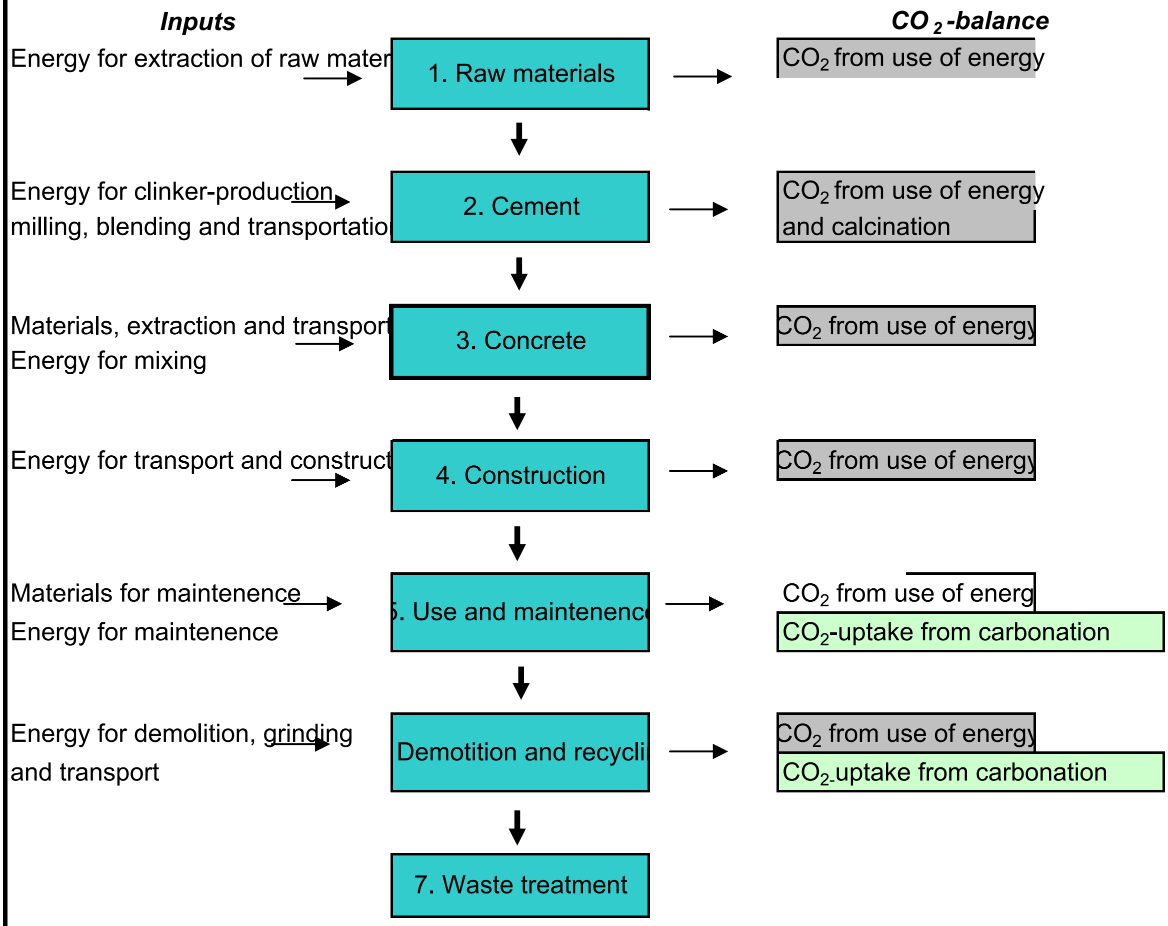
The clinker in the concrete above consists of

Calcium oxide (kg)	32,5
Others (kg)	17,5

Raw materials

Limestone, pure (kg)	58,0
Others (kg)	17,5
Gypsum	2,6
Fly ash	0,00
Blast funce slag	0,00

2. Life cycle steps



Go throught the following sheets.
Correct and fill out data where necessary.

3. Extraction of raw materials

In this section the emissions of carbon dioxide from the use of energy for extraction of the raw materials are calculated.

The emissions of carbon dioxide from consumption of electricity depend on the basis resources used, and this varies through out Europe. Therefore the location of the extraction has to be defined.
As default value an European avarage is used, - this can be used if no specific information is available.

A: Extraction of raw materials for cement production

Electricity Location	kg CO_2 per kWh	Component Others (kg)	Fly ash	Gypsum	Blast funce s	0	Limestone, pure (kg)
Denmark	0,753	1	1	1	1	1	1
Finland	0,352	0	0	0	0	0	0
Iceland	0	0	0	0	0	0	0
Norway	0	0	0	0	0	0	0
Sweden	0,036	0	0	0	0	0	0
Nordic avarage	0,147	0	0	0	0	0	0
EU-25 avarage	0,475	0	0	0	0	0	0

Components	kg per unit	Electricity [kWh/ton]	Oil [kg/ton]	Gas [m^3/ton]	CO_2 kg/unit
Others (kg)	17,48	0	1	0	0,063
Fly ash	0,00	0	1	0	0,000
Gypsum	2,63	0	1	0	0,009
Blast funce slag	0,00	0	1	0	0,000
0	0	0	0	0	0,000
Limestone, pure (kg)	57,99	0	1	0	0,208
In total	78,10				0,072

B: Extraction of raw materials for Concrete production

Electricity Location	kg CO_2 per kWh	Component Fly ash	Fine aggre	Coarse agg	Others	0	0	Water
Denmark	0,753	1	1	1	1	1	1	1
Finland	0,352	0	0	0	0	0	0	0
Iceland	0	0	0	0	0	0	0	0
Norway	0	0	0	0	0	0	0	0
Sweden	0,036	0	0	0	0	0	0	0
Nordic average	0,147	0	0	0	0	0	0	0
EU-25 average	0,475	0	0	0	0	0	0	0

Components	kg per unit	Electricity [kWh/ton]	Oil [kg/ton]	Gas [m^3/ton]	CO_2 kg/unit
Fly ash	29,828	0	0,01	0	0,001
Fine aggregates	127,930	0	1,5	0	0,689
Coarse aggregates	256,303	0	1	0	0,920
Others	5,966	0	0	0	0,000
0	0,000	0	0	0	0,000
0	0,000	0	0	0	0,000
Water	29,386	0,1	0	0	0,002
In total					1,612

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4. Transport from extraction site to cement plant

All raw materials used for cement production have to be transported from extraction site to the cement plant.
Therefore, it is necessary to know the average distance to the extraction site for limestone and other raw materials.
It is also necessary to know the transport mode (truck, rail or ship)

In the table below some defalt values are given, - these can be changed if more specific data are availeble

Transportation to clinker production

CO_2 per ton x km [kg] Components	kg per unit	Distance Total km	Truck 16 tons 0,228	Truck 40 tons 0,093	Rail Electric 0,029	Rail E+Diesel 0,03	Ship oceanic 0,008	Ship inland 0,039	CO_2 per unit (kg)
Others (kg)	17,48	0	0	100	0	0	0	0	0,163
Fly ash	0,00	0	0	100	0	0	0	0	0,000
Gypsum	0,00	0	50	0	0	0	0	0	0,000
Blast funce slag	0,00	0	0	100	0	0	0	0	0,000
Limestone, pure (kg)	57,99	10	0	10	0	0	0		0,054
In total	75,47								0,217

Transportation to cement production

CO_2 per ton x km [kg] Components	kg per unit	Distance total km	Truck 16 tons 0,228	Truck 40 tons 0,093	Rail Electric 0,029	Rail E+Diesel 0,03	Ship oceanic 0,008	Ship inland 0,039	CO_2 per unit (kg)
Clinker	49,96	0	0	0	0	0	0	0	0,000
Fly ash	0,00	100	0	100	0	0	0	0	0,000
Gypsum	2,63	50	0	50	0	0	0	0	0,012
Blast funce slag	0,00	100	0	100	0	0	0	0	0,000
0	0,00	0	0	0	0	0	0	0	0,000
In total	52,59								0,012

Total emittet CO_2 kg per unit	
Transport to clinker production	0,217
Transport to cement production	0,012
Step 4, sum	0,229

5. Production of cement

Emission of carbon dioxide from production of cement consists of several contributions, - it includes emissions from energy used for heating the clinker kiln, - from calcination, from grinding the clinker to cement

In the table below some defalt values are given, - these can be changes if more specific data is availeble

CO_2 emissions from calcination depend on the amount of $CaCO_3$ in the raw materials

From 1 kg calcium carbonate (pure limestone) 0,44 kg CO_2 is emitted

Production of 1 kg of calciumoxide in clinker causes the emission of 0,786 kg CO_2.

Content of pure limestone (kg)	58,0
Calcium oxide (kg)	32,5
CO_2 from calcination (kg)	25,5

If the above number seems incorrect, it is possible to correct it here :

Calcium oxide (kg)	32,5
CO_2 corrected	25,5

The emissions of carbon dioxide from the consumption of electricity depend on the basis resources used, and this varies through out Europe. Therefore the location of the cement plant has to be defined.
As default value an European avarage is used, - this can be used if no specific information is available.

Electricity Location	kg CO_2 per kWh	
Denmark	0,753	0
Finland	0,352	0
Iceland	0	0
Norway	0	0
Sweden	0,036	0
Nordic average	0,147	0
EU-25 average	0,475	1

Amount of cement per unit (kg)	52,59
Calcium oxide (kg)	32,47
Amount of clinker per unit (kg)	49,96

	Hard coal [kg/ton]	Lignite [kg/ton]	Oil [kg /ton]	Gas [m3/ton]	Electricity [kwh/ton]	Renew-ables	Others	CO_2 (kg) per unit
kg CO2 per kg or m3	3,98	2,95	3,59	2,29	0,475	0	0	
Clinker production	200		35	9,5	0	0	0	47,130
Grinding			0	0	0	0	0	0,000
Blending			0	0	0	0	0	0,000
Others			0	0	0	0	0	0,000
In total								47,130

Total emitted CO_2 kg per unit	
Calcination	25,523
Other processes	47,130
Step 5, sum	72,653

6. Transport of materials to the concrete plant

All materials used for concrete production has to be transported from the extraction site or the cement plant.
Therfore, it is necessary to know the average distance to extraction site for aggregates and other raw materials.
It is also necessary to know the transport mode (truck, rail or ship)

In the table below some defalt values are given, - these can be changed if more specific data is available

CO_2 per ton x km [kg] Components	kg per unit	Distance Total km	Truck 16 tons 0,228	Truck 40 tons 0,093	Rail Electric 0,029	Rail E+Diesel 0,03	Ship oceanic 0,008	Ship inland 0,039	CO_2 per unit (kg)
Cement	52,6	100	0	100	0	0	0	0	0,489
Fly ash	29,8	50	50	0	0	0	0	0	0,340
Fine aggregates	127,9	10	0	10	0	0	0	0	0,119
Coarse aggregates	256,3	10	0	10	0	0	0	0	0,238
Others	6,0	0	1	0	0	0	0	0	0,001
0	0,0	0	1	0	0	0	0	0	0,000
0	0,0	0	1	0	0	0	0	0	0,000
Water	29,4	0	1	0	0	0	0	0	0,007
Total									1,194

Total emitted CO_2 kg per unit	
Transportation	1,194
Step 6, sum	1,194

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7. Production of concrete

Mixing of concrete consumes energy. The type and amount of energy may vary from plant to plant.

Below some defalt values are given, which can be changed if specific data are available.

The emissions of carbon dioxide from consumption of electricity depend on the basis resources used, and this varies through out Europe. Therefore the location of the concrete plant has to be defined.
As default value an European avarage is used, - this can be used if no specific information is available

Electricity Location	kg CO_2 per kWh	
Denmark	0,753	0
Finland	0,352	0
Iceland	0	0
Norway	0	0
Sweden	0,036	0
Nordic average	0,147	0
EU-25 average	0,475	1

Amount of concrete kg/unit 502

	Oil [kg /ton]	Gas [m^3/ton]	Electricity [kwh/ton]	Renew-ables	Others	CO_2 (kg) per unit
kg CO_2 kg or m^3	3,59	2,29	0,475	0	0	
Mixing	5	0	0	0	0	9,011
Others	0	0	0	0	0	0,000
Total						9,011

8. Transport from concrete plant to construction s

The concrete has to be transported to the construction site. Data for the average distance is necessary.
It is also necessary to know the transport mode (truck, rail or ship)

In the table below some defalt values are given, - these can be changed, if more specific data is available

CO_2 per ton x km [kg]	kg per unit	Distance total km	Truck 16 tons 0,228	Truck 40 tons 0,093	Rail Electric 0,029	Rail E+Diesel 0,03	Ship oceanic 0,008	Ship inland 0,039	CO_2 per unit (kg)
Concrete	502	25	0	25	0	0	0	0	1,167

9. Construction

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Conctruction may consume energy. The type and amount of energy may vary from situation to situatio

Below some defalt values are given, which can be changed if specific data are available.

The emissions of cabon dioxide from consumption of electricity depend on the basis resources used, and this varies through out Europe. Therefore the location of the concrete plant has to be defined. As default value is used a European avarage, - this can be used if no specific information is availeble.

Electricity Location	kg CO_2 per kWh	
Denmark	0,753	0
Finland	0,352	0
Iceland	0	0
Norway	0	0
Sweden	0,036	0
Nordic average	0,147	0
EU-25 average	0,475	1

Amount of concrete kg/unit 502

	Oil [kg /ton]	Gas [m^3/ton]	Electricity [kwh/ton]	Renew-ables	Others	CO_2 (kg) per unit
kg CO_2 kg or m^3	3,59	2,29	0,475	0	0	
Concrete placement	0,5	0		0	0	0,901
Others	0	0	0	0	0	0,000
Total						0,901

10. Use and maintenance

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The primary change in this life cycle step is the inclusion of uptake of carbon dioxide from carbonisation. Data for carbonisation is measured in practice and data for various types of cement and constructions are available.

This step in the life cycle does not include heating if the construction is a house or similar construction.

Therefore, this step includes consumed energy for maintenance and carbon dioxide uptake. Materials for maintenance is not included. Only emissions from energy is included.

Energy

Electricity Location	kg CO_2 per kWh	
Denmark	0,753	0
Finland	0,352	0
Iceland	0	0
Norway	0	0
Sweden	0,036	0
Nordic average	0,147	0
EU-25 average	0,475	1

Amount of concrete kg/unit 502

Maintenance	Oil [kg /ton]	Gas [m^3/ton]	Electricity [kwh/ton]	Renew-ables	Others	CO_2 (kg) per unit
kg CO_2 kg or m^3	3,59	2,29	0,475	0	0	
Mixing	0	0	0	0	0	0,000
Others	0	0	0	0	0	0,000
Total						0,000

Carbon dioxide uptake

Estimation of the uptake of carbon dioxide during use is based on the rate of carbonation, the number of years and the surface of the unit.

The time is given by the service life. The surface can be calculated or given in m^2

The rate of carbonation depend on the type of concrete, environmental exposure and other parameters, - these can be determined in the following procedure:

Service life (years) 70

Unit weight (kg) 502

Surface of the construction: Can be calculated as the volume times two divided by the thickness or given as an actual figure.

Thickness of the unit (m) 0,2

Area (m^2) 2,21

Change the surface area here if necessary 2,21

Type of concrete, strength and environmental class

Choose the category by putting a "1" in the right cell	Exposed	Sheltered	Indoors	Wet	Buried
Old concrete and some concrete products like cement bo	0	0	0	0	0
15- 20 MPa, Old houses and some products	0	0	0	0	0
25-35 MPa, Most houses today	0	0	0	0	0
> 35 MPa, Most infrastructure concrete	1	0	0	0	0

Continues

10. Use and maintenance

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Correction factor for strength and environmental class:

K1 (mm)	1

Correction for surface treatment and cover, -
Choose the category by putting a "1" in the right cell

Indoor house concrete	0
Outdoor house concre	0
Infra structure concret	1
K2	1

Correction factors for types of supplementary material, -
-Choose the category by putting a "1" in the right cell

Type	
5-10 % silica fume	0
15 % limestone	0
30% limestone	0
15% fly ash	0
30% fly ash	1
20 % GBFS	0
40% GBFS	0
60 % GBFS	0
K3	1,1

K (mm)	1,1

Depth of carbonation is :	D (mm)	9	D(m)	0,009	
Volume carbonated	V (m3)	0,020339	Max Volume (m3)		0,220951
Amount of CO2-uptake (kg)	1,761				

11. Demolition and recycling

During demolition and preparation for recycling energy is used in equipment, etc. The fraction for recycling is ground into smaller particles. After grinding the surface of the concrete is very large, and the uptake of carbon dioxide will take place much faster.

To estimate the emission and uptake of carbon dioxide the rate of recycling, the consumption of energy and the size of particles have to be determined.

Fraction of recycling (%) **90**

Energy

Electricity Location	kg CO_2 per kWh	
Denmark	0,753	0
Finland	0,352	0
Iceland	0	0
Norway	0	0
Sweden	0,036	0
Nordic average	0,147	0
EU-25 average	0,475	1

Demolition includes the whole unit equal to 502 kg
Grinding includes the part for recycling 451,8 kg

	Oil [kg /ton]	Gas [m^3/ton]	Electricity [kwh/ton]	Renew-ables	Others	CO_2 (kg) per unit
kg CO_2 per kg or m^3	3,59	2,29	0,475	0	0	
Demolition	2	0	0	0	0	3,604
Grinding	2		1	0	0	3,459
Total						7,063

The following is assumed for the particle sizes of the demolished and ground concrete

	percent	Sizes (mm	Av. D. (m)	percentage
Recycled Material	90	<1	0,001	20
		1-10	0,005	30
		10-30	0,020	45
		>30	0,050	5
Landfilled	10	> 100	0,100	100

0,75

The K-value to be used is for buried environment and is only determined by the strength class

< 15 Mpa	0
15-20 Mpa	0
25-35 mPA	0
>35 Mpa	1
K=	0,75

Lifespan for carbonation of demolished material(years) 30

Depth of carbonation (mm) 4,1

All perticles with a diameter of 8,2 mm will be fully carbonated.

11. Demolition and recycling

Calculation of carbonated volume

Total volume of unit (m^3)	0,221	Depth of carbonation (m)	0,0041
Carbonated volume during service life	0,020		

Volume of particles < 1 mm (m^3)	0,040
Volume of particles 1 - 10 mm (m^3)	0,060
Volume of particles 10 - 30 mm (m^3)	0,089
Volume of particles > 30 mm (m^3)	0,010

Material not recycled, diameter of particles D=10(	0,022

Carbonated volume

Particles	<1 mm	R1=	0,0005	R2=	-0,003607919	Vol=	0,040	
Particles	1-10 mm	R1=	0,0025	R2=	-0,001607919	Vol=	0,060	
Particles	10-30 mm	R1=	0,01	R2=	0,005892081	Vol=	0,071	
Particles	>30 mm	R1=	0,025	R2=	0,020892081	Vol=	0,004	
Particles	> 100 mm	R1=	0,05	R2=	0,045892081	Vol=	0,005	

Carbonated volume	0,180	81,35714
Carbonated during service life	0,020	

Uptake of carbondioxide (kg) =	14,128

12. Transport of demolished materials

Recycled and landfilled material has to be transported. Data for the average distance is necessary.
It is also necessary to know the transport mode (truck, rail or ship)

In the table below some default values are given, - these can be changes if more specific data is available

	kg per unit	Distance total	Truck 16 tons	Truck 40 tons	Rail Electric	Rail E+Diesel	Ship oceanic	Ship inland	CO_2 per unit
CO_2 per ton x km [kg]		km	0,228	0,093	0,029	0,03	0,008	0,039	(kg)
Recycled material	451,8	25	0	25	0	0	0	0	1,050
Landfilled material	50,2	25	25	0	0	0	0	0	0,286
In total (kg)									1,337

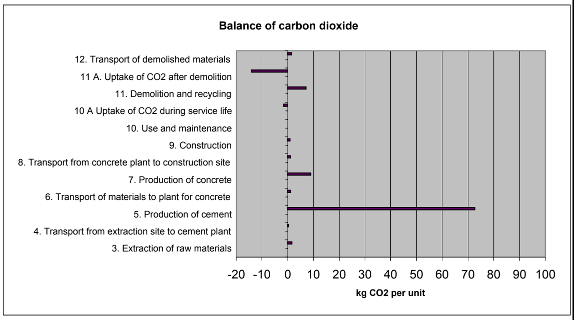
Results

In the following all the emissions and uptake of carbon dioxide from the life cycle are presented.
Assumptions, omissions and specific details can be seen at the sheet for the specific life cycle phase.

For a contruction of 0,50 Tonnes per unit the following CO_2-ballance has been estimated.

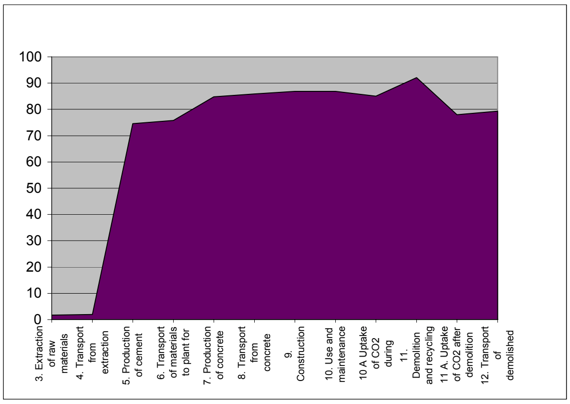
	kg CO_2 per unit	Acc kg CO_2 per unit
3. Extraction of raw materials	1,685	1,685
4. Transport from extraction site to cement plant	0,229	1,913
5. Production of cement	72,653	74,566
6. Transport of materials to plant for concrete	1,194	75,760
7. Production of concrete	9,011	84,771
8. Transport from concrete plant to construction site	1,167	85,938
9. Construction	0,901	86,840
10. Use and maintenance	0,000	86,840
10 A Uptake of CO_2 during service life	-1,761	85,079
11. Demolition and recycling	7,063	92,142
11 A. Uptake of CO_2 after demolition	-14,128	78,014
12. Transport of demolished materials	1,337	79,350
In total	79,350	

Emission from calcination	25,523	kg CO_2 per unit
Uptake from carbonation	15,889	kg CO_2 per unit
Max theoretical uptake (75% of CaO)	19,126	kg CO_2 per unit



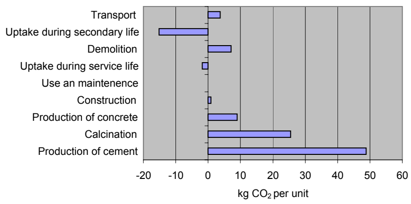
83,07327

3. Extraction of raw materials	1,685
4. Transport from extraction site to cement plant	1,913
5. Production of cement	74,566
6. Transport of materials to plant for concrete	75,760
7. Production of concrete	84,771
8. Transport from concrete plant to construction site	85,938
9. Construction	86,840
10. Use and maintenance	86,840
10 A Uptake of CO2 during service life	85,079
11. Demolition and recycling	92,142
11 A. Uptake of CO2 after demolition	78,014
12. Transport of demolished materials	79,350

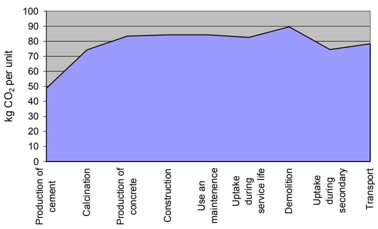


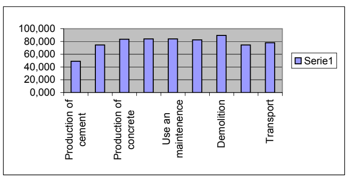
3. Extraction of raw materials	1,68
4. Transport from extraction site to cement plant	0,07
5. Production of cement	72,65
6. Transport of materials to plant for concrete	1,19
7. Production of concrete	9,01
8. Transport from concrete plant to construction site	1,17
9. Construction	0,90
10. Use and maintenance	0,00
10 A Uptake of CO_2 during service life	-1,76
11. Demolition and recycling	7,06
11 A. Uptake of CO_2 after demolition	####
12. Transport of demolished materials	1,34
	78,2

Production	48,814
Calcination	25,523
Production	9,01
Constructio	0,90
Use an mai	0,00
Uptake dur	-1,76
Demolition	7,06
Uptake dur	-15,12
Transport	3,76
	78,199



Production	48,814
Calcination	74,337
Production	83,348
Constructio	84,249
Use an mai	84,249
Uptake dur	82,489
Demolition	89,551
Uptake dur	74,435
Transport	78,199





Appendix C

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Balance of carbon dioxide

emissions and up-take during the concrete life cycle

In this spread sheet the balance of carbon dioxide can be calculated for a concrete item in its life cycle.

The spread sheet consists of several sheets, -an introduction and some pages, where the activities in the life cycle are described.
Default values are given and can be changed by the user. Background data should not be changed.

The pages included in this folder are:
1. Definition of the product
2. Definition of the life cycle steps
3. Extraction of raw materials ½
4. Transport from extraction site to cement plant
5. Production of cement
6. Transport of materials to plant for concrete
7. Production of concrete
8. Transport from concrete plant to construction site
9. Construction
10. Use and maintenance
11. Demolition and recycling
12. Transport of demolished materials

Limitations and omissions
Interactions with other systems - has to be determined
Reinforcement has not been included
Heating from the use-phase (no. 10) has not been included

Use of the spread sheet:
The spread sheet has been designed with data for 10 m2 of pavers as an example.
Work trough the 13 pages and consider adequate changes with respect to the actual product.
Data that may be changed are marked with a remark.

All the sheets are designed so that they can easily can be printed for documentation.

1. Product definition

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Define the functional unit, first by a brief description, then by some exact data.
The function of the product is ……..

Functional unit:
The product is 1 m^2 of roof tiles.

Service life time	50	years
Weight	0,04	tons per unit
Quality		
Other properties		

Composition of the concrete

Components	Per m3 (kg)	Per unit (kg)
Cement	480	8,4
Fly ash	0	0,0
Fine aggregates	1760	30,7
Coarse aggregates	0	0,0
Others	2	0,0
		0,0
		0,0
Water	166	2,9
In total	2408	42,0

Materials for production of 1 tonne of cement

Components [kg per ton]	Portland cement	Type 1	Type 2	Type 3	Actual	Per unit
Clinker	950				917	7,68
Limestone filler	0				40	0,33
Gypsum	50				37	0,31
Iron sulfate					6	0,05
						0,00
In total	1000				1000	8,37

Materials for production of 1 tonne of clinker
Pecent of calcium oxide in clinker 65

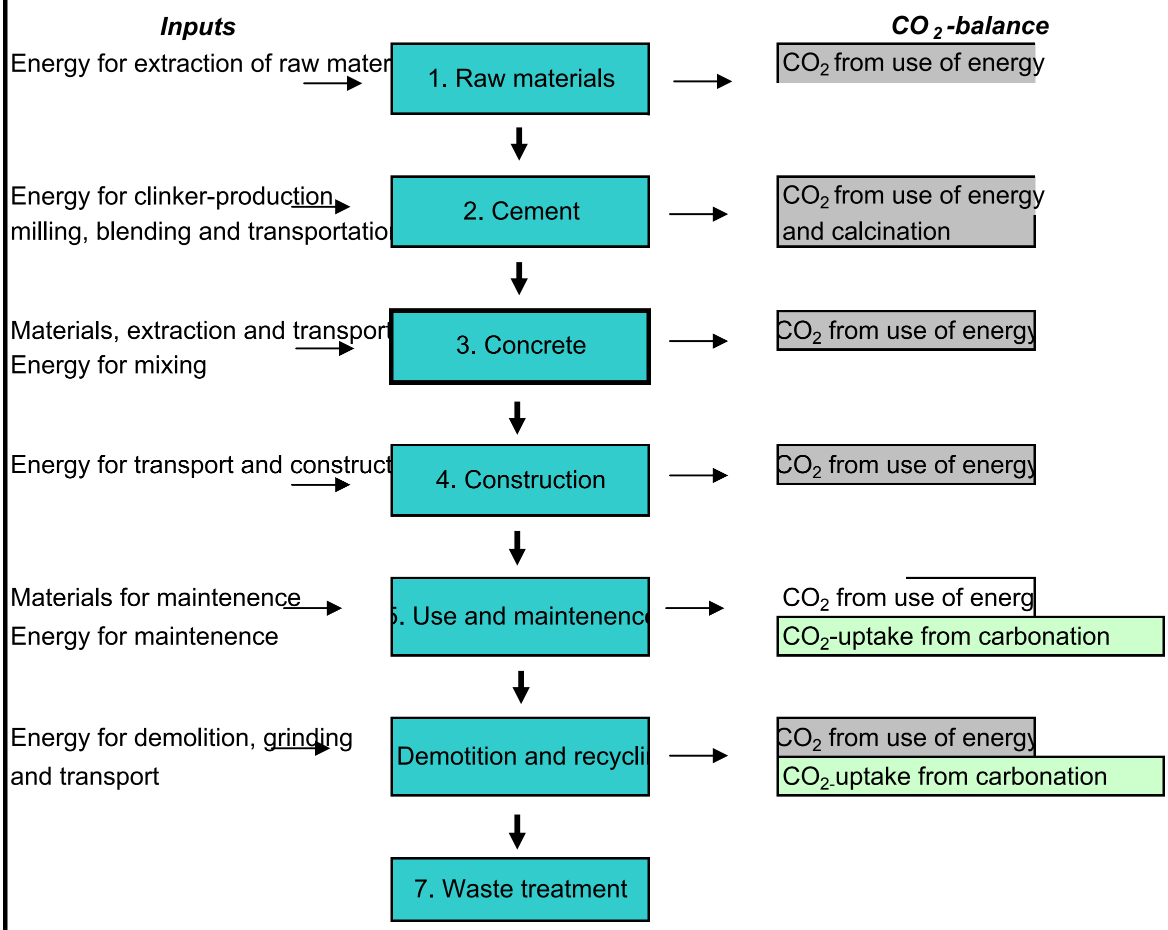
The clinker in the concrete above consists of

Calcium oxide (kg)	5,0
Others (kg)	2,7

Raw materials

Limestone, pure (kg)	8,9
Others (kg)	2,7
Gypsum	0,3
Limestone filler	0,33
Iron sulfate	0,05

2. Life cycle steps



Go throught the following sheets.
Correct and fill out data where necessary.

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3. Extraction of raw materials

In this section the emissions of carbon dioxide from the use of energy for extraction of the raw materials are calculated.

The emissions of carbon dioxide from consumption of electricity depend on the basis resources used, and this varies through out Europe. Therefore the location of the extraction has to be defined.
As default value an European avarage is used, - this can be used if no specific information is available.

A: Extraction of raw materials for cement production

Electricity Location	kg CO_2 per kWh	Component Others (kg)	Limestone	Gypsum	Iron sulfate	0	Limestone, pure (kg)
Denmark	0,753	1	1	1	1	1	1
Finland	0,352	0	0	0	0	0	0
Iceland	0	0	0	0	0	0	0
Norway	0	0	0	0	0	0	0
Sweden	0,036	0	0	0	0	0	0
Nordic avarage	0,147	0	0	0	0	0	0
EU-25 avarage	0,475	0	0	0	0	0	0

Components	kg per unit	Electricity [kWh/ton]	Oil [kg/ton]	Gas [m^3/ton]	CO_2 kg/unit
Others (kg)	2,69	0	1	0	0,010
Limestone filler	0,33	0	1	0	0,001
Gypsum	0,31	0	1	0	0,001
Iron sulfate	0,05	0	1	0	0,000
0	0	0	0	0	0,000
Limestone, pure (kg)	8,91	0	1	0	0,032
In total	12,29				0,012

B: Extraction of raw materials for Concrete production

Electricity Location	kg CO_2 per kWh	Component Fly ash	Fine aggre	Coarse agg	Others	0	0	Water
Denmark	0,753	1	1	1	1	1	1	1
Finland	0,352	0	0	0	0	0	0	0
Iceland	0	0	0	0	0	0	0	0
Norway	0	0	0	0	0	0	0	0
Sweden	0,036	0	0	0	0	0	0	0
Nordic average	0,147	0	0	0	0	0	0	0
EU-25 average	0,475	0	0	0	0	0	0	0

Components	kg per unit	Electricity [kWh/ton]	Oil [kg/ton]	Gas [m^3/ton]	CO_2 kg/unit
Fly ash	0,000	0	0,01	0	0,000
Fine aggregates	30,698	0	1,5	0	0,165
Coarse aggregates	0,000	0	1	0	0,000
Others	0,035	0	0	0	0,000
0	0,000	0	0	0	0,000
0	0,000	0	0	0	0,000
Water	2,895	0,1	0	0	0,000
In total					0,166

4. Transport from extraction site to cement plant

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All raw materials used for cement production have to be transported from extraction site to the cement plant.
Therefore, it is necessary to know the average distance to the extraction site for limestone and other raw materials.
It is also necessary to know the transport mode (truck, rail or ship)

In the table below some defalt values are given, - these can be changed if more specific data are availeble

Transportation to clinker production

CO_2 per ton x km [kg] Components	kg per unit	Distance Total km	Truck 16 tons 0,228	Truck 40 tons 0,093	Rail Electric 0,029	Rail E+Diesel 0,03	Ship oceanic 0,008	Ship inland 0,039	CO_2 per unit (kg)
Others (kg)	2,69	0	0	100	0	0	0	0	0,025
Limestone filler	0,00	0	0	100	0	0	0	0	0,000
Gypsum	0,00	0	50	0	0	0	0	0	0,000
Iron sulfate	0,05	0	0	0	0	0	0	0	0,000
Limestone, pure (kg)	8,91	10	0	10	0	0	0		0,008
In total	11,65								0,033

Transportation to cement production

CO_2 per ton x km [kg] Components	kg per unit	Distance total km	Truck 16 tons 0,228	Truck 40 tons 0,093	Rail Electric 0,029	Rail E+Diesel 0,03	Ship oceanic 0,008	Ship inland 0,039	CO_2 per unit (kg)
Clinker	7,68	0	0	0	0	0	0	0	0,000
Limestone filler	0,33	100	0	100	0	0	0	0	0,003
Gypsum	0,31	50	0	50	0	0	0	0	0,001
Iron sulfate	0,05	100	0	100	0	0	0	0	0,000
0	0,00	0	0	0	0	0	0	0	0,000
In total	8,37								0,005

Total emittet CO_2 kg per unit	
Transport to clinker production	0,033
Transport to cement production	0,005
Step 4, sum	0,038

5. Production of cement

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Emission of carbon dioxide from production of cement consists of several contributions, - it includes emissions from energy used for heating the clinker kiln, - from calcination, from grinding the clinker to cement

In the table below some defalt values are given, - these can be changes if more specific data is availeble

CO_2 emissions from calcination depend on the amount of $CaCO_3$ in the raw materials

From 1 kg calcium carbonate (pure limestone) 0,44 kg CO_2 is emitted
Production of 1 kg of calciumoxide in clinker causes the emission of 0,786 kg CO_2.

Content of pure limestone (kg)	8,9
Calcium oxide (kg)	5,0
CO_2 from calcination (kg)	3,9

If the above number seems incorrect, it is possible to correct it here :

Calcium oxide (kg)	5,0
CO_2 corrected	3,9

The emissions of carbon dioxide from the consumption of electricity depend on the basis resources used, and this varies through out Europe. Therefore the location of the cement plant has to be defined.
As default value an European avarage is used, - this can be used if no specific information is available.

Electricity Location	kg CO_2 per kWh	
Denmark	0,753	0
Finland	0,352	0
Iceland	0	0
Norway	0	0
Sweden	0,036	0
Nordic average	0,147	0
EU-25 average	0,475	1

Amount of cement per unit (kg)	8,37
Calcium oxide (kg)	4,99
Amount of clinker per unit (kg)	7,68

	Hard coal [kg/ton]	Lignite [kg/ton]	Oil [kg /ton]	Gas [m3/ton]	Electricity [kwh/ton]	Renew-ables	Others	CO_2 (kg) per unit
kg CO2 per kg or m3	3,98	2,95	3,59	2,29	0,475	0	0	
Clnker production	66		5	0	0	0	0	2,154
Grinding			0	0	0	0	0	0,000
Blending			0	0	0	0	0	0,000
Others			0	0	0	0	0	0,000
In total								2,154

Total emitted CO_2 kg per unit	
Calcination	3,922
Other processes	2,154
Step 5, sum	6,077

6. Transport of materials to the concrete plant

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All materials used for concrete production has to be transported from the extraction site or the cement plant.
Therfore, it is necessary to know the average distance to extraction site for aggregates and other raw materials.
It is also necessary to know the transport mode (truck, rail or ship)

In the table below some defalt values are given, - these can be changed if more specific data is available

CO_2 per ton x km [kg] Components	kg per unit	Distance Total km	Truck 16 tons 0,228	Truck 40 tons 0,093	Rail Electric 0,029	Rail E+Diesel 0,03	Ship oceanic 0,008	Ship inland 0,039	CO_2 per unit (kg)
Cement	8,4	100	0	100	0	0	0	0	0,078
Fly ash	0,0	50	50	0	0	0	0	0	0,000
Fine aggregates	30,7	10	0	10	0	0	0	0	0,029
Coarse aggregates	0,0	10	0	10	0	0	0	0	0,000
Others	0,0	0	1	0	0	0	0	0	0,000
0	0,0	0	1	0	0	0	0	0	0,000
0	0,0	0	1	0	0	0	0	0	0,000
Water	2,9	0	1	0	0	0	0	0	0,001
Total									0,107

Total emitted CO_2 kg per unit	
Transportation	0,107
Step 6, sum	0,107

7. Production of concrete

Mixing of concrete consumes energy. The type and amount of energy may vary from plant to plant.

Below some defalt values are given, which can be changed if specific data are available.

The emissions of carbon dioxide from consumption of electricity depend on the basis resources used, and this varies through out Europe. Therefore the location of the concrete plant has to be defined.
As default value an European avarage is used, - this can be used if no specific information is available

Electricity Location	kg CO_2 per kWh	
Denmark	0,753	0
Finland	0,352	0
Iceland	0	0
Norway	0	0
Sweden	0,036	0
Nordic average	0,147	0
EU-25 average	0,475	1

Amount of concrete kg/unit 42

	Oil [kg /ton]	Gas [m^3/ton]	Electricity [kwh/ton]	Renew-ables	Others	CO_2 (kg) per unit
kg CO_2 kg or m^3	3,59	2,29	0,475	0	0	
Mixing	5	0	0	0	0	0,754
Others	0	0	0	0	0	0,000
Total						0,754

8. Transport from concrete plant to construction s

The concrete has to be transported to the construction site. Data for the average distance is necessary.
It is also necessary to know the transport mode (truck, rail or ship)

In the table below some defalt values are given, - these can be changed, if more specific data is available

CO_2 per ton x km [kg]	kg per unit	Distance total km	Truck 16 tons 0,228	Truck 40 tons 0,093	Rail Electric 0,029	Rail E+Diesel 0,03	Ship oceanic 0,008	Ship inland 0,039	CO_2 per unit (kg)
Concrete	42	100	0	100	0	0	0	0	0,391

9. Construction

Conctruction may consume energy. The type and amount of energy may vary from situation to situatio

Below some defalt values are given, which can be changed if specific data are available.

The emissions of cabon dioxide from consumption of electricity depend on the basis resources used, and this varies through out Europe. Therefore the location of the concrete plant has to be defined. As default value is used a European avarage, - this can be used if no specific information is availeble.

Electricity Location	kg CO_2 per kWh	
Denmark	0,753	0
Finland	0,352	0
Iceland	0	0
Norway	0	0
Sweden	0,036	0
Nordic average	0,147	0
EU-25 average	0,475	1

Amount of concrete kg/unit 42

	Oil [kg /ton]	Gas [m^3/ton]	Electricity [kwh/ton]	Renew-ables	Others	CO_2 (kg) per unit
kg CO_2 per kg or m^3	3,59	2,29	0,475	0	0	
Concrete placement	0,5	0		0	0	0,075
Others	0	0	0	0	0	0,000
Total						0,075

10. Use and maintenance

The primary change in this life cycle step is the inclusion of uptake of carbon dioxide from carbonisation.
Data for carbonisation is measured in practice and data for various types of cement and constructions are available.

This step in the life cycle does not include heating if the construction is a house or similar construction.

Therefore, this step includes consumed energy for maintenance and carbon dioxide uptake.
Materials for maintenance is not included. Only emissions from energy is included.

Energy

Electricity Location	kg CO_2 per kWh	
Denmark	0,753	0
Finland	0,352	0
Iceland	0	0
Norway	0	0
Sweden	0,036	0
Nordic average	0,147	0
EU-25 average	0,475	1

Amount of concrete kg/unit 42

Maintenance	Oil [kg /ton]	Gas [m^3/ton]	Electricity [kwh/ton]	Renew-ables	Others	CO_2 (kg) per unit
kg CO_2 per kg or m^3	3,59	2,29	0,475	0	0	
Mixing	0	0	0	0	0	0,000
Others	0	0	0	0	0	0,000
Total						0,000

Carbon dioxide uptake
Estimation of the uptake of carbon dioxide during use is based on the rate of carbonisation, the number of years and the surface of the unit.
The time is given by the service life. The surface can be calculated or given in m^2
The rate of carbonation depend on the type of concrete, environmental exposure and other parameters, - these can be determined in the following procedure:

Service life (years) 50
Unit weight (kg) 42

Surface of the construction: Can be calculated as the volume times two divided by the thickness or given as an actual figure.

Thickness of the unit (m) 0,02

Area (m^2) 1,74
Change the surface area here if necessary 2

Type of concrete, strength and environmental class

Choose the category by putting a "1" in the right cell	Exposed	Sheltered	Indoors	Wet	Buried
Old concrete and some concrete products like cement bo	0	0	0	0	0
15- 20 MPa, Old houses and some products	0	0	0	0	0
25-35 MPa, Most houses today	0	0	0	0	0
> 35 MPa, Most infrastructure concrete	1	0	0	0	0

Continues

10. Use and maintenance

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Correction factor for strength and environmental class:

K1 (mm) 1

Correction for surface treatment and cover, -
Choose the category by putting a "1" in the right cell

Indoor house concrete	0
Outdoor house concre	0
Infra structure concrete	1
K2	1

Correction factors for types of supplementary material, -
Choose the category by putting a "1" in the right cell

Type	
5-10 % silica fume	0
15 % limestone	1
30% limestone	0
15% fly ash	0
30% fly ash	0
20 % GBFS	0
40% GBFS	0
60 % GBFS	0
K3	1,05

K (mm) 0,37

Depth of carbonation is :	D (mm)	3	D(m)	0,003		
Volume carbonated	V (m3)	0,005233	Max Volume (m3)		0,017442	30,00018
Amount of CO2-uptake (kg)	0,882					

11. Demolition and recycling

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During demolition and preparation for recycling energy is used in equipment, etc. The fraction for recycling is ground into smaller particles. After grinding the surface of the concrete is very large, and the uptake of carbon dioxide will take place much faster.

To estimate the emission and uptake of carbon dioxide the rate of recycling, the consumption of energy and the size of particles have to be determined.

Fraction of recycling (%) **90**

Energy

Electricity Location	kg CO_2 per kWh	
Denmark	0,753	0
Finland	0,352	0
Iceland	0	0
Norway	0	0
Sweden	0,036	0
Nordic average	0,147	0
EU-25 average	0,475	1

Demolition includes the whole unit equal to 42 kg
Grinding includes the part for recycling 37,8 kg

	Oil [kg /ton]	Gas [m^3/ton]	Electricity [kwh/ton]	Renew-ables	Others	CO_2 (kg) per unit
kg CO_2 per kg or m^3	3,59	2,29	0,475	0	0	
Demolition	2	0	0	0	0	0,302
Grinding	2		1	0	0	0,289
Total						0,591

The following is assumed for the particle sizes of the demolished and ground concrete

	percent	Sizes (mm	Av. D. (m)	percentage
Recycled Material	90	<1	0,001	20
		1-10	0,005	30
		10-30	0,020	45
		>30	0,050	5
Landfilled	10	> 100	0,100	100

0,75

The K-value to be used is for buried environment and is only determined by the strength class

< 15 Mpa	0
15-20 Mpa	0
25-35 mPA	0
>35 Mpa	1
K=	0,37

Lifespan for carbonation of demolished material(years) 50

Depth of carbonation (mm) 2,6

All perticles with a diameter of 5,2 mm will be fully carbonated.

11. Demolition and recycling

Calculation of carbonated volume

Total volume of unit (m^3)	0,017	Depth of carbonation (m)	0,0026
Carbonated volume during service life	0,005		
Volume of particles < 1 mm (m^3)	0,003		
Volume of particles 1 - 10 mm (m^3)	0,005		
Volume of particles 10 - 30 mm (m^3)	0,007		
Volume of particles > 30 mm (m^3)	0,001		
Material not recycled, diameter of particles D=10(	0,002		

Carbonated volume

Particles	<1 mm	R1=	0,0005	R2=	-0,002116295	Vol=	0,003
Particles	1-10 mm	R1=	0,0025	R2=	-0,000116295	Vol=	0,005
Particles	10-30 mm	R1=	0,01	R2=	0,007383705	Vol=	0,004
Particles	>30 mm	R1=	0,025	R2=	0,022383705	Vol=	0,000
Particles	> 100 mm	R1=	0,05	R2=	0,047383705	Vol=	0,000

Carbonated volume	0,013	71,95578
Carbonated during service life	0,005	41,9556

Uptake of carbondioxide (kg) = 1,480

12. Transport of demolished materials

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Recycled and landfilled material has to be transported. Data for the average distance is necessary.
It is also necessary to know the transport mode (truck, rail or ship)

In the table below some default values are given, - these can be changes if more specific data is available

	kg per unit	Distance total	Truck 16 tons	Truck 40 tons	Rail Electric	Rail E+Diesel	Ship oceanic	Ship inland	CO_2 per unit
CO_2 per ton x km [kg]		km	0,228	0,093	0,029	0,03	0,008	0,039	(kg)
Recycled material	37,8	25	0	25	0	0	0	0	0,088
Landfilled material	4,2	25	25	0	0	0	0	0	0,024
In total (kg)									0,112

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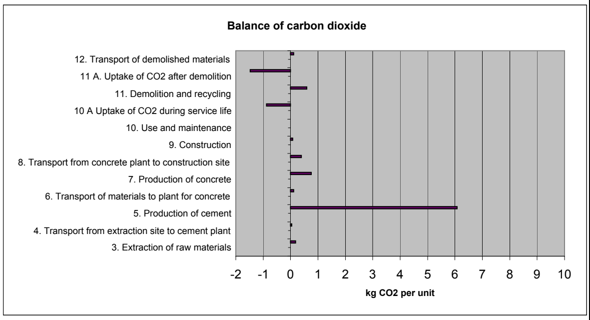
Results

In the following all the emissions and uptake of carbon dioxide from the life cycle are presented.
Assumptions, omissions and specific details can be seen at the sheet for the specific life cycle phase.

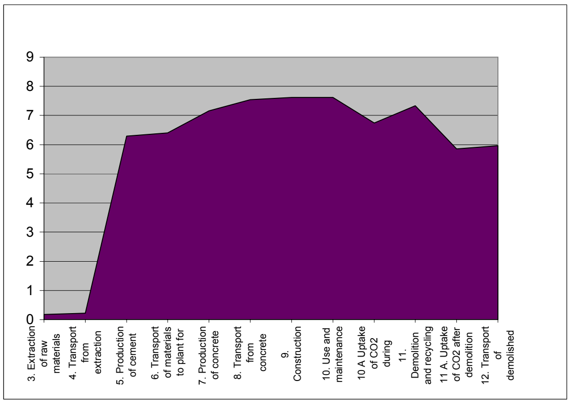
For a contruction of 0,04 Tonnes per unit the following CO_2-ballance has been estimated.

	kg CO_2 per unit	Acc kg CO_2 per unit
3. Extraction of raw materials	0,178	0,178
4. Transport from extraction site to cement plant	0,038	0,216
5. Production of cement	6,077	6,293
6. Transport of materials to plant for concrete	0,107	6,400
7. Production of concrete	0,754	7,154
8. Transport from concrete plant to construction site	0,391	7,544
9. Construction	0,075	7,620
10. Use and maintenance	0,000	7,620
10 A Uptake of CO_2 during service life	-0,882	6,738
11. Demolition and recycling	0,591	7,329
11 A. Uptake of CO_2 after demolition	-1,480	5,848
12. Transport of demolished materials	0,112	5,960
In total	5,960	

Emission from calcination	3,922	kg CO_2 per unit
Uptake from carbonation	2,362	kg CO_2 per unit
Max theoretical uptake (75% of CaO)	2,939	kg CO_2 per unit

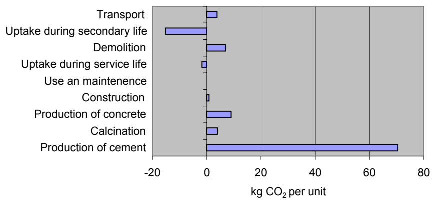


3. Extraction of raw materials	0,178
4. Transport from extraction site to cement plant	0,216
5. Production of cement	6,293
6. Transport of materials to plant for concrete	6,400
7. Production of concrete	7,154
8. Transport from concrete plant to construction site	7,544
9. Construction	7,620
10. Use and maintenance	7,620
10 A Uptake of CO2 during service life	6,738
11. Demolition and recycling	7,329
11 A. Uptake of CO2 after demolition	5,848
12. Transport of demolished materials	5,960



3. Extraction of raw materials	1,68
4. Transport from extraction site to cement plant	0,07
5. Production of cement	72,65
6. Transport of materials to plant for concrete	1,19
7. Production of concrete	9,01
8. Transport from concrete plant to construction site	1,17
9. Construction	0,90
10. Use and maintenance	0,00
10 A Uptake of CO_2 during service life	-1,76
11. Demolition and recycling	7,06
11 A. Uptake of CO_2 after demolition	-15,12
12. Transport of demolished materials	1,34
	78,2

Production	70,415
Calcination	3,922
Production	9,01
Constructio	0,90
Use an mai	0,00
Uptake dur	-1,76
Demolition	7,06
Uptake dur	-15,12
Transport	3,76
	78,199



Production	70,415
Calcination	74,337
Production	83,348
Constructio	84,249
Use an mai	84,249
Uptake dur	82,489
Demolition	89,551
Uptake dur	74,435
Transport	78,199