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Improving the CO₂ performance of cement, part I: Utilizing life-cycle assessment and key performance indicators to assess development within the cement industry

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Abstract

Cement is a vital and commonly used construction material that requires large amounts of resources and the manufacture of which causes significant environmental impact. However, there are many different types of cement products, roughly ranging from traditional products with rather linear resource flows to more synergistic alternatives where industrial byproducts are utilized to a large extent. Life Cycle Assessment (LCA) studies indicate the synergistic products are favorable from an environmental perspective.

In co-operation with the global cement producing company CEMEX a research project has been carried out to contribute to a better understanding of the CO₂ performance of different ways of producing cement, and different cement products. The focus has been on Cluster West, which is a cement production cluster consisting of three plants in Germany.

This paper is the first in a series of three, all of which are included in this special issue. It has two main aims. The first is to carry out an attributional LCA and compare three different cement products produced in both linear and synergistic production setups. This has been done for cradle to gate, focusing on CO₂-eq emissions for Cluster West. The second aim of this part is to develop and test a simplified LCA model for this production cluster, with the intention to be able to compare different versions of the production system based on the information of a few parameters.

The attributional LCA showed that cement products that contain a large proportion of byproducts, in this case, ground granulated blast furnace slag from the iron and steel industry, had the lowest unit emissions of CO₂-eq. The difference between the lowest emission product (CEM III/B) and the highest (CEM I) was about 66% per tonne. A simplified LCA model based on six key performance indicators, instead of approximately 50 parameters for the attributional LCA, was established. It showed that Cluster West currently emits about 45% less CO₂-eq per tonne of average product compared to 1997. The simplified LCA model can be used effectively to model future changes of both plants and products (which is further discussed in part II and part III).

Keywords: cement production, life cycle assessment, CO₂ emissions, modeling, performance indicators

1 Introduction

In co-operation with the global cement producing company CEMEX S.A.B. de C.V. (CEMEX) a research project has been carried out to contribute to a better understanding of the CO₂ emissions of different ways of producing cement, and different cement products, applying Life Cycle Assessment (LCA).

This paper is the first in a series of three, all of which are included in this special issue. The second paper presents a systematic approach for assessing measures to reduce the CO₂ emissions related to the

cement industry (Feiz et al., 2013)¹. The third article, based on the other two, focuses on the relevance of industrial symbiosis when striving towards improved CO₂ performance of cement (Ammenberg et al., 2013)².

1.1 Cement and cement production

Cement is in many ways an essential material that is used worldwide, mainly as a component of concrete. In 2009 the estimated yearly production of cement exceeded 3 billion tonnes and this figure continued to grow during 2010 and 2011 (van Oss, 2012), corresponding to about 0.5 tonne of cement produced per person on the planet each year.

Cement production and use is highly energy and material intensive (Bernstein et al., 2007; Boesch et al., 2009; Reijnders, 2007; van Oss and Padovani, 2002), and of high environmental importance, e.g., causing more than 5% of the global anthropogenic CO₂ emissions and substantial emissions of SO₂, NO_x and other pollutants (EIPPCB, 2010; IEA/WBCSD, 2009; van Oss and Padovani, 2003, 2002).

The most common form of cement is Portland cement, about 93-97% of which consists of a material called clinker. Clinker is formed when the raw material limestone burns at a high temperature in a cement kiln (van Oss and Padovani, 2002). In this process calcium carbonate decomposes and CaO and CO₂ is produced (Worrell et al., 2001). This is called calcination and it is highly important from a greenhouse gas emission perspective, since in the process carbon bound in minerals is transformed into CO₂ (Chen et al., 2010). The calcination typically causes more than 50% of total CO₂ emissions from cement production, and a large share of the remaining emissions originates from combustion of the fuels in the kiln (Huntzinger and Eatmon, 2009). The clinker is then ground to a fine powder and blended with gypsum or similar sulfates and perhaps other additives (e.g., air-entraining agents, pigments).

In addition to Portland cement, there are other types of hydraulic cements and several formal categorization systems to define them. The ASTM standard in the USA (2013) and the European cement standard EN 197-1 (2011) are widely used. The latter standard defines five main types of cement (CEM I to V), where each main type has a few sub-types, ending up with 27 different cement types in total. The main distinguishing factor between these types is their material content. CEM I has the highest amount of clinker, corresponding to Portland cement. Other types have lower clinker content and instead alternative materials are used, referred to as “supplementary cementitious materials” (SCM). These materials act either as pozzolans (non-cementitious siliceous materials that become hydraulically cementitious when reacted with free lime) or latent cements (weakly hydraulically cementitious materials that become strongly cementitious when reacted with lime) and thus can partially replace clinker. They are ground and blended (mixed) in the required proportions in order to produce different types of cement. Examples of materials used as clinker substitutes are byproducts such as ground granulated blast furnace slag³ (GGBFS) from the iron and steel industry and fly ash from coal-fired power plants.

Figure 1 shows a simplified overview of common clinker/cement production and also illustrates how clinker is replaced by (for example) GBFS for blended cement types.

¹ From now on referred to as “part II”

² From now on referred to as “part III”

³ GBFS is a residue from blast furnace production of crude iron and it can be used as a raw material feed to produce clinker. Ground GBFS (abbreviated GGBFS) can partially substitute for clinker in blended cements, or similarly, substitute for cement when making concrete.

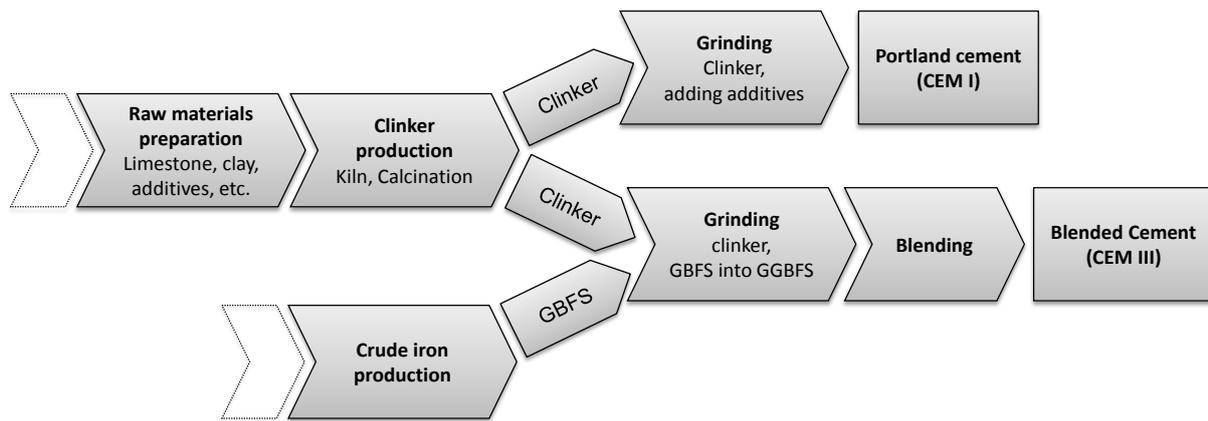


Figure 1. A simplified overview of how clinker is partly replaced by supplementary cementitious materials such as GGBFS for producing blended cement.

1.2 Life cycle assessment of cement

Life Cycle Assessments (LCA) are commonly used to study the environmental impacts from the cement industry (Chen et al., 2010; Lu, 2010; Ortiz et al., 2009) and such studies are important to learn more about this industry and about strategies for reducing the impact. For example, these studies tell us that the production of ordinary Portland cement commonly results in CO₂ emissions exceeding 0.9 tonnes CO₂/tonne cement and that each tonne of cement might require input of 1.5-1.6 tonnes of raw materials, 3000-4300+ MJ of fuel energy and 120-160 kWh of electrical energy (EIPPCB, 2013; Nicolas and Jochen, 2008; Price et al., 2010). Furthermore, LCA studies can be utilized to assess and compare the environmental performance of the different types of cement mentioned (Gäbel and Tillman, 2005; Strazza et al., 2011; Valderrama et al., 2012; Van den Heede and De Belie, 2012). However, full scale and detailed LCA studies (in compliance with the ISO 1404x standards) is complicated and time consuming (Wenzel et al., 1997) and thus costly, to gather all the data needed and find case-specific information of good quality. If the production involves several cement plants, in the form of an industrial cluster, the task grows. Such projects tend to require more sophisticated and well-structured LCA approaches, to handle several external links to material and fuel suppliers while simultaneously having intermediate links between different plants within the cluster. In many cases it is also desirable to be able to handle development within a cement production system, such as changes in technology, fuel and raw materials. But dynamics in the production systems lead to changes in the Life Cycle Inventory (LCI) which may lead to updating of many parameters and data inside an already complicated model.

The problems mentioned are of course not specific to LCA studies of cement. The need for simplified LCA methods is evident in many industrial sectors and different ways of streamlining the LCA process is commonly mentioned in literature, see (Bretz, 1998; Fleischer et al., 2001; Hochschorner and Finnveden, 2003; Mueller et al., 2004; Ross and Evans, 2002; Soriano, 2004; Sun et al., 2004). There are several ways of simplifying the LCA process, for example, to:

- Exclude some data and/or mainly focus on some key indicators.
- Use generic data instead of case specific data.
- Exclude some environmental impact categories.
- Exclude some parts of the life cycle.
- Apply qualitative LCA methods.

This paper presents a study that is based on a detailed, quantitative LCA of cement (attributorial LCA), which is then utilized to develop a simplified LCA model.

1.3 A studied case

CEMEX is a global manufacturer and supplier of building materials operating in more than 50 countries and the company is one of the largest cement producers in the world. In cooperation, researchers from Linköping University, Sweden, and staff from CEMEX during a one-year project have studied the cement production at Cluster West in Germany.

Cluster West consists of three plants – Kollenbach (in Beckum); Dortmund (in Dortmund) and Schwelgern (in Duisburg). They form a kind of work alliance, together producing several intermediate and final products. Kollenbach and Schwelgern are about 100 km apart and Dortmund is located almost in the middle. Figure 2 gives an overview of important material and energy flows, including:

- Inbound flows - mainly raw materials, fuels and electricity
- Internal flows - clinker, GBFS, and various intermediate products
- Outbound flows - final cement products. Concerning Cluster West, the focus has been on the different cement products (CEM I-III), and not on other products such as ready-mix concrete.

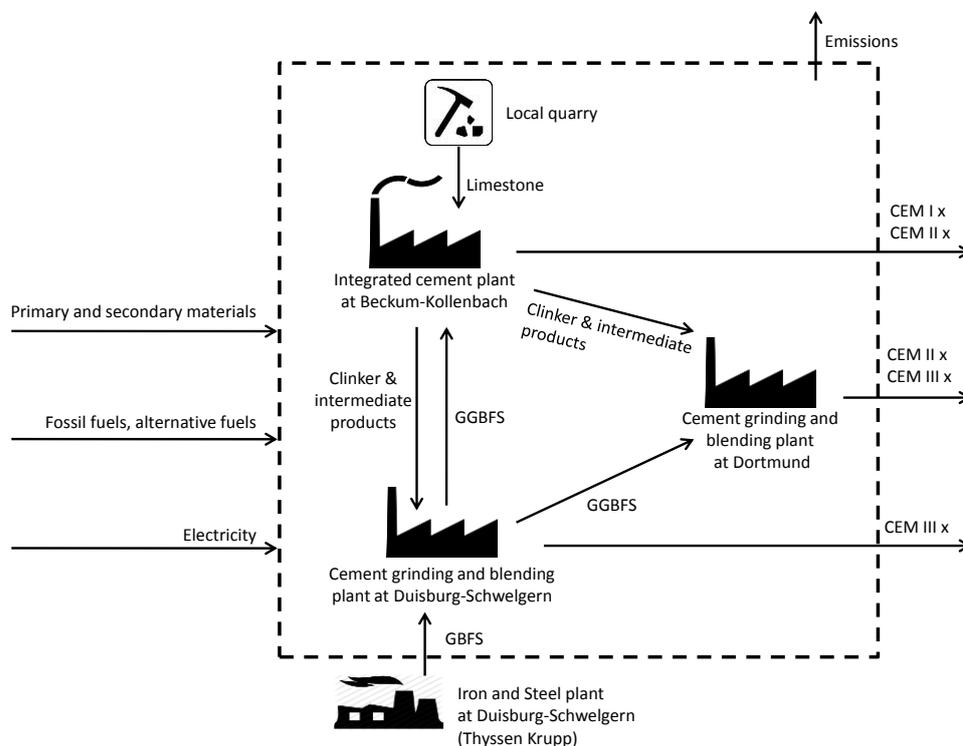


Figure 2. Overview of the CEMEX Cluster West in 2009.

CEMEX owns a local quarry of lime marl at Kollenbach (in Beckum) with estimated reserves enough for 30 years, considering the 2009 production rate. The marl is motor transported to the plant. In addition, high grade limestone is delivered by train from suppliers situated within a range of about 50 km. The Kollenbach plant is an integrated cement plant, manufacturing clinker, several intermediate products (mainly composed of clinker) and different types of cement with high proportions of clinker (such as CEM I or CEM II). It has a rotary kiln ahead of which is a four-stage cyclone preheater, but no precalciner. The kiln is equipped with a rotary (drum) clinker cooler. It was modified in 2000 and 2001 and was then equipped with a feeding system for secondary fuels. There is a vertical roller mill as rawmill and two ball mills as cement mills. The Kollenbach plant has a good record of technological innovation, for instance, in 1953 the first cyclone preheater in the world was installed. In 2009, the clinker production was about 0.8 million tonnes and more than half of it (as clinker or intermediate products) was shipped to the Dortmund and Schwelgern plants for production of various blended cements. In this year the main fuels were refused derived fuels (RDF) such as fluff (36.8% of total heat input to the kiln) and animal meal (28.0%), and fossil fuels such as coal (24.7%).

Schwelgern is a grinding and blending plant (no kiln, no clinker production, two cement ball mills) at Duisburg, that is co-located with the Thyssen Krupp Iron and Steel plant, producing steel and getting blast furnace slag as a byproduct. At the steel plant the slag is quenched by water, converting it to granulated blast furnace slag (GBFS) and delivered to CEMEX/Schwelgern where it is ground into GGBFS⁴. Due to its cementitious properties GGBFS can partly substitute for clinker. For example, products such as CEM III (depending on their sub-types) can have between 36 to 95% GGBFS in their composition. Direct application of the cement with extremely high GGBFS content (such as 95%) may be limited, but it can be used for further blending into a concrete mix. The annual cement production capacity of the Schwelgern plant is about 1 million tonnes. Various types of so-called blast furnace cement (CEM III) are produced such as CEM III/A and CEM III/B having different properties and GGBFS contents.

Similar to Schwelgern, the Dortmund plant is a grinding and blending mill (no kiln, no clinker production, two cement ball mills) with an annual cement production capacity of about 1 million tonnes. Here the products such as clinker (or other intermediates containing clinker) from Kollenbach along with GBFS from Schwelgern are milled and mixed in special silos in order to produce various cement products, mainly CEM III/A. Most of the GBFS at Schwelgern is shipped to the Dortmund plant.

The three plants in total produced about 1.8 million tonnes of cement products in 2009, consisting of about 8% CEM I, 3% CEM II, 55% CEM III/A, and 34% CEM III/B. Among different products which were produced in the Cluster West three products were selected. The cement products that have been studied were selected in cooperation with CEMEX. The intention was to choose products with a clearly different share of clinker substitutes, which means ranging from high clinker content (i.e., pure clinker and Portland cement) to blended cement products where a substantial part of the clinker is substituted by GGBFS. In addition, the selection was also made to be able to study old and future production. The selected products are CEM I, CEM III/A and CEM III/B (all grade 42.5). As clinker is an important (intermediate) product, it is included in the study and treated as if it was a finished product. However it should be noted that Cluster West does not sell clinker on the market; it is used for internal production. More information about the project and the plants is available in Ammenberg et al. (2011).

1.4 Aim

This paper aims to assess the global warming potential for clinker and the following selected cement products:

- CEM I 42.5 - also called Portland cement, with around 92% clinker content⁵ (the number 42.5 refers to the fineness of the cement).
- CEM III/A 42.5 - a blended cement type with around 50% clinker content. It includes GGBFS as a supplementary cementitious material.
- CEM III/B 42.5 - a blended cement type with around 27% clinker content. It includes GGBFS as a supplementary cementitious material).

This is done in detail for the year 2009 (regarded as the present situation), by conducting an attributional comparative life cycle assessment (LCA), applying a “cradle-to-gate perspective” and using the functional unit of 1 tonne of cement produced.

In addition, it is investigated if a simplified LCA model can be developed and applied to assess the global warming potential for different versions of the production system and other cement products. The model shall be based on a few key performance indicators, but still have a reasonable accuracy. The aim is not to completely avoid a full attributional LCA study, but rather to use the simplified

⁴ In the papers (parts I-III) we sometimes use GGGBFS to stress that we mean the finely ground fraction. Otherwise, GBFS is used, both for actual GBFS and GGBFS.

⁵ This rather low clinker content, for this type of product, is explained by additives, for example, bypass dust.

model for several purposes. For example, it could significantly facilitate an assessment of possible future versions of Cluster West.

2 Methodology

Here the case and the LCA-based methodology are presented in more detail. The original LCA study was carried out as a typical attributional and comparative LCA in line with the ISO 14040 and 14044 standards (see ISO 14040, 2006; ISO 14044, 2006).

2.1 CEMEX Cluster West production system

An overview of the central material and energy flows in 2009 is given in Figure 2. The inbound flows generally consist of primary and secondary nonfuel raw materials, fossil and alternative fuels, electricity and for two of the three plants, clinker. The internal flows are clinker, GBFS and intermediate products. As the intermediate products are required to produce the selected products assessed, they have been modeled in detail with complete life cycle data inventories and are accounted for in the LCA. However, they are not specified in this paper⁶. Furthermore, the outbound flows consist of several finished cement products ready to be shipped to market.

This means that all intermediate products have been modeled in detail, with complete life cycle data inventories, in the original LCA (step 1).

2.2 Scope and functional unit

In agreement with CEMEX it was decided to focus on the initial parts of the life cycle, from “cradle to gate,” including extraction of raw materials, production/upgrading of materials, manufacturing of cement and transportation within this scope. There are several reasons for this choice. Cement can be used in many different ways in a variety of concrete structures. There is also limited information available on the lifespan of concrete structures and the subsequent processes. A broadened scope focusing on concrete would have been much more complex and it appears to be a common choice to apply a cradle-to-gate perspectives in LCA studies of cement (Boesch and Hellweg, 2010; Chen et al., 2010; Huntzinger and Eatmon, 2009; Josa et al., 2004). However, Kapur et al. (2008) have modeled the end of life phase of concrete.

The functional unit was defined as *1 tonne of cement product*, which was seen as reasonable since the scope does not include the use phase meaning that the key service delivered by cement is not included. This choice was also important to be able to realize the aim and assess several cement products with a broad range of qualities. The choice of functional unit is also in line with several other studies (Boesch et al., 2009; Josa et al., 2004). However, it is important to keep in mind that different cement products have a different composition.

Biogenic CO₂ emissions are excluded from the formal CO₂ emissions reporting of cement producers in Germany. The CO₂ neutrality concerning the biogenic fraction of fuels is controversial depending on their origin and chosen temporal scope. For simplicity, we have assumed that biogenic CO₂ does not contribute to global warming, in line with the IPCC GWP100 model (IPCC, 2007).

2.3 Data collection

Site-specific data were collected for each plant, comprising types and amounts of energy and fuels, raw materials, products, emissions and waste. A majority of the data was for 2009, considered as the “present situation,” since it was the most current information available when the project started. In addition, some information about the sites for 1997 has been used to estimate emissions from previous production. CEMEX provided detailed information about the composition of the intermediate and

⁶ For information about this intermediate production refer to Ammenberg et al. (2011).

finished cement products. In addition, the company provided data about heat values of fuels, transportation and CO₂ emission factors for combustion of the fuels at Kollenbach.

A rather extensive input/output tool was created to facilitate the management of the data. It provided structure and was needed to convert and link the inputs/outputs, originally expressed in annual figures for each plant, to the functional unit.

CEMEX has mainly provided data about the flows within the cluster as well as inbound and outbound flows. However, the scope of the LCA study was cradle to gate and the Ecoinvent LCA database (Ecoinvent, 2012) has been used to include the upstream parts of the life cycle for which CEMEX could not provide the needed information. For example, data from Ecoinvent were used for animal meal, refuse-derived fuel fluff (RDF fluff) and tires.

In this study the environmental impacts associated with infrastructure such as construction of the plants or other supporting infrastructure such as roads, railroads, electricity networks and the like were not included. However, a test was performed to estimate the impact of this exclusion, by using generic information from the Ecoinvent database. It showed that the impact of including infrastructural processes in the LCA model concerning clinker production increased the overall CO₂-eq emissions by less than 1%, indicating that the exclusion was reasonable in this case.

To facilitate the choice of generic data and secure good data quality an evaluation method by Weidema & Wesnæs (Weidema and Wesnæs, 1996) was applied. The influence of the generic data sets was tested and for data of importance the research team made a data quality check in line with the mentioned methodology, then decided whether site-specific data should be requested instead. In order to estimate the influence of data uncertainty on the results of the LCA, an uncertainty analysis was performed on the data from statistical sources and not on the data received directly from CEMEX. The site-specific information did not contain any uncertainty ranges (such as standard deviation and other descriptors). The generic data from the Ecoinvent LCA database was described with uncertainty ranges and thus was included in the uncertainty analysis. The uncertainty analysis was performed by applying 95% confidence interval. The uncertainty range in all the studied products was less than 5% of their corresponding emissions.

Several previous LCA studies of cement are based on generic data from LCA databases as the primary data source. To calculate the elementary flows regarding the upstream processes almost all identified LCA studies have utilized LCA databases, especially regarding the emissions related to upstream processes (Boesch and Hellweg, 2010; Boesch et al., 2009; Chen et al., 2010; Huntzinger et al., 2009; Nisbet and Van Geem, 1997; Pade and Guimaraes, 2007). Consequently, the impression is that this project is based on more case-specific data than many other similar studies.

2.4 Allocation

Inbound materials and fuels originating from upstream product systems where they are considered waste, have not been accounted any environmental impact in this study. The burden of waste is accounted for its producers. Nevertheless, transportation of these (“waste”) materials and fuels has been included and also impact caused by treatment and upgrading processes where they were carried out to make the materials or fuels suitable for CEMEX. Such examples are:

- Animal meal and bone meal (MBM) - a special fraction of slaughterhouse waste.
- All RDF-fluff materials - waste fractions from the municipal waste treatment that has been grinded and mixed together.
- Shredded tires - discarded tires are being shredded.
- Granulated Blast Furnace Slag (GBFS) - the blast furnace slag has been granulated to be suitable.

For several reasons the GBFS requires special attention. GBFS can be considered a byproduct, since unlike the others it has not been handled as a waste by definition and it can be bought on a market. In

addition, the amounts of GBFS are much higher than those for other “waste materials” and it is related to the steel industry contributing to significant environmental impact. Consequently, it is reasonable to argue that more impact should be allocated to this material than only the minor impact caused when granulating the slag (i.e., mainly cooling it with water).

In the attributional LCA that formed the foundation of the study, only the impact caused by upgrading was considered. But to complement the picture, economic allocation was carried out for the GBFS. This means that a portion of the CO₂-eq emissions from the upstream product system, which is the production of crude iron, has been allocated to the GBFS. Generally, the choice of allocation principles is controversial and can have a large influence on the final results (Reap et al., 2008; Van den Heede and De Belie, 2012). In the reviewed LCA studies of cement, allocation is handled in different ways. Some studies have choices similar to those of this study (Boesch and Hellweg, 2010; Chen et al., 2010), while others use system expansion (Lee and Park, 2005) or do not clarify this issue (Flower and Sanjayan, 2007; Huntzinger and Eatmon, 2009; Navia et al., 2006; Nisbet and Van Geem, 1997).

2.5 Simplified LCA model

In addition to the original attributional LCA model, focusing on 2009 and the selected products, the intention was to create and test a simplified model that could be used to analyze other cement products and dynamics in the production system. The simplified LCA model was developed in a three-step process shown in Figure 3. All LCA models were created and calculated using the LCA software *SimaPro*, ver.7.3.

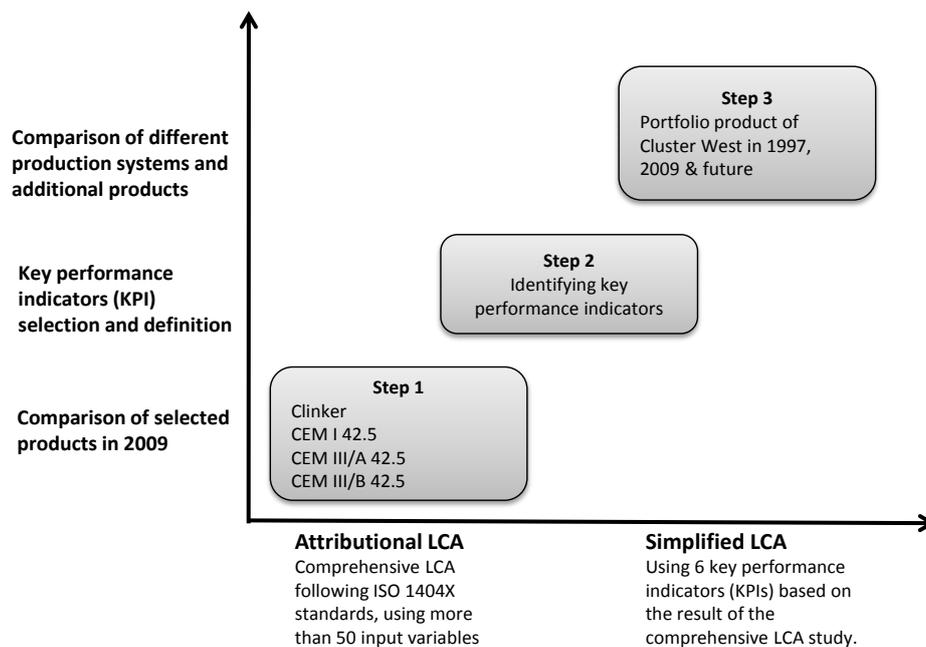


Figure 3. Illustration of the main steps of the method, going from the attributional to a simplified LCA model for analyzing different products as well as production systems.

The first step is the attributional LCA previously described: It was based on a thorough life cycle inventory and included more than 50 different input variables.

The second step tested whether any parameters were of special importance, referred to as Key Performance Indicators (KPI). If a few such parameters can be found that provide most of the information needed, the complexity of the problem can be reduced significantly without losing too much accuracy. Such influential parameters concerning the CO₂ emissions existed and were identified:

- KPI₁: The share of clinker substitutes in an average cement product, called the *Cluster West portfolio cement* (further explained below).

- KPI₂: CO₂ emissions from production of 1 tonne of clinker due to calcination.
- KPI₃: CO₂ emissions from combustion of fuels which is represented by the amount of thermal energy required to produce 1 tonne of clinker.
- KPI₄: the share of renewable fuels, which is the biogenic fraction of the alternative fuels (assumed to be CO₂-neutral in this study) (percentage of heat generated from biogenic fuels).
- KPI₅: CO₂ emissions due to production of electricity, which is represented by the amount of electricity used for production of 1 tonne of the *Cluster West portfolio cement* (the average cement product).
- KPI₆: the share of renewable electricity.

This means that several of the KPIs are defined as aggregate indicators for the production system of Cluster West, while KPI₂ and KPI₃ concern the clinker production at the Kollenbach plant.

In step 3, the simplified model was developed based on the KPIs. The cement products as well as the Cluster West production system change over time. To be able to model and assess such dynamics the virtual (average) *Cluster West portfolio cement* was used, defined as the weighted average of all the finished cement products. For example, the clinker substitution rate of the portfolio cement was calculated as the weighted average of all products. It seemed reasonable to model the Cluster West portfolio cement as a product consisting of only clinker, clinker substitutes (mainly GBFS in this case) and “others” (any other additives that are part of the product). Important reasons behind this choice were the facts that the clinker production contributed to the majority of the CO₂ emissions and that GBFS was used extensively. Together clinker and clinker substitutes (mainly GBFS) represented about 90-95% of the total mass of the final product. Step 3 transformed the production system into a simplified system that only produced clinker and the virtual Cluster West portfolio cement - see Figure 4.

The energy input was modeled by creating representative parameters, without specifying each fuel in detail (coal, oil, etc.). Instead, it was seen as an “energy mix,” consisting of a share of a “fuel mix” and an “electricity mix.” Further on, these two parts consisted of a “renewable fuel mix” and a “non-renewable fuel mix,” and a “renewable electricity mix” and a “non-renewable electricity mix,” respectively. It was also assumed that the composition of each of these mix-fuels or mixed types of electricity generation, and their corresponding emissions from Cluster West in 2009, was representative for all other assessed time periods as well. The changes in emissions attributed to changes in energy sources were reflected by changing the share of the renewable fuel mix of the total fuel mix, and the share of the electricity mix of the total energy mix.

To establish how each KPI influenced the results a sensitivity analysis of the LCA model was conducted by slightly changing each KPI and noting the influence on the resulting CO₂ emissions. Assuming that the inputs of the model were the KPIs and the output was the total life cycle CO₂ emissions per tonne of portfolio cement, the sensitivity analysis was performed by changing each KPI 1%, 5%, 10% and 20% (in direction for CO₂ reduction) and calculating the result. Having established how each KPI influenced the CO₂ emissions it was possible to utilize the simplified model for estimation of Cluster West’s CO₂-eq emissions based on figures for the six KPIs. To the accuracy of the simplified model, the results were compared with those of the original LCA for clinker and the selected products.

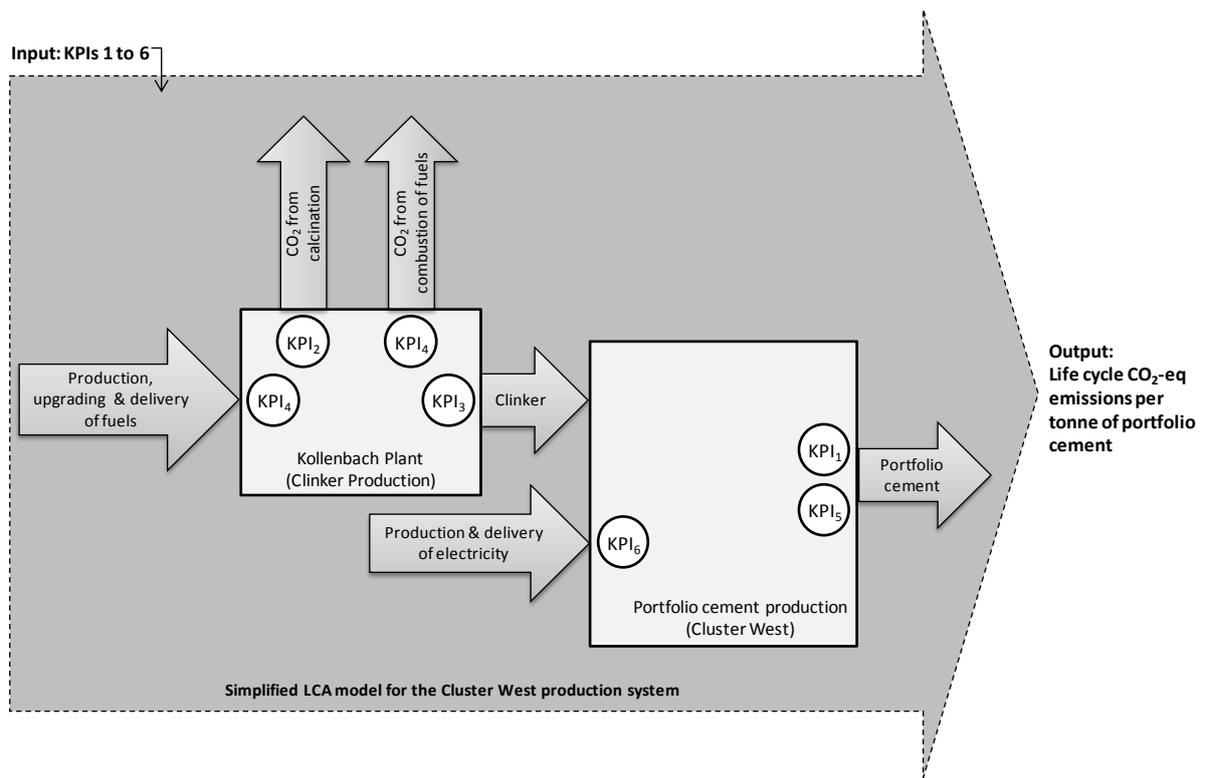


Figure 4. The simplified LCA model that is based on the Key Performance Indicators (KPIs) and the simplified production system of Cluster West, only producing clinker and the virtual portfolio cement (the average cement product).

The simplified LCA model was used to assess Cluster West as it was in 1997. For that purpose CEMEX provided the needed information (for KPI₁₋₆), i.e., data about the energy input (fuel and electricity) and production. The results concerning 1997 were thus calculated by changing several of the KPIs according to the production conditions of 1997. For instance, KPI₁ changed due to a lower rate of clinker substitution and KPI₄ was changed to reflect that the share of renewable fuels was lower in 1997.

3 Comparison of products

As mentioned, the attributional LCA was based on the thorough inventory. It showed that a majority of direct inputs of raw materials to Cluster West were related to the production of clinker at the Kollenbach plant. Most of the fuel is burned at the kiln there. Only small amounts of fossil fuels, i.e., natural gas and coke gas, are used for the production of CEM III/A 42.5 and CEM III/B 42.5. Electricity is used for the production of all products in all plants. Milling of clinker or GBFS (into GGBFS) accounted for a considerable share of the electricity in all plants, especially in the Schwelgern and Dortmund plants where no clinker is produced.

Table 1 shows a summary of the composition of the selected products and the results of the cradle to gate LCA (step 1 in Figure 3). It contains information about the composition in terms of clinker, clinker substitutes (assumed to be GBFS in Cluster West) and other materials (such as gypsum and other additives). In addition to these selected products, similar calculations have been done for the intermediate products but they are not shown in this table (Ammenberg et al., 2011).

Table 1. Unit CO₂-eq emissions for the selected cement products from Cluster West in 2009 and also the virtual, average product – Cluster West Portfolio Cement.

Cement products	Production plant	Clinker-to-cement ratio (%)	GBFS-to-cement ratio	Other contents (%)	Clinker substitution rate (%)	Unit CO ₂ emissions (kg
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		(%)				CO ₂ /tonne)
Clinker	Kollenbach	100	0	0	0	850
CEM I 42.5	Kollenbach	90	0	10	10	779
CEM III/A 42.5	Dortmund	47	45	8	53	452
CEM III/B 42.5	Schweglern	25	70	5	75	265
Portfolio Cement	Cluster West	40	53	7	60	385

Within the cement industry benchmarking is often based on figures concerning clinker, where the global warming potential for Cluster West was found to be 850 kg CO₂. This could be compared to the world average, which according to Moya et al. (2010) is in the range 900-1000 kg CO₂ per tonne.

Almost 90% of the CO₂ emissions for clinker are linked to the production process of the Kollenbach plant (Table 2), to a large extent explained by the calcination corresponding to about 64%. Based on the CaO content of clinker (66.3%) the CO₂ calcination emissions were estimated at 520 kg CO₂/tonne clinker. CEMEX has estimated the emissions due to calcination to be slightly higher and about 525 kg CO₂/tonne clinker and in order to account for the bypass dust and other factors, an additional 3% was added, ending up with 541 kg CO₂ for each tonne of clinker produced (adapted from guidelines of IPCC, 1997).

The second and third most contributing processes can also be found within the Kollenbach plant - the combustion of kiln coal and RDF fluff (silo) that emitted about 10% and 8% respectively. This was not surprising since relatively large amounts of these fuels are combusted. The part of the life cycle where raw materials are extracted, upgraded and transported to the plant contributed to 12% of CO₂ emissions for clinker. This was mainly due to the electricity used for production of clinker and the upgrading of animal meal that is used as alternative fuel. Each contributed about 5% of the total emissions. Together, the transportation contributed to less than 0.5% of the total impact.

Table 2. CO₂-eq emissions from the different processes in the life cycle of clinker.

Life cycle phase	Process	Consumed		Emissions	Share	
		unit / tonne clinker		kg CO ₂ -eq / tonne clinker	%	
	Electricity (German mix)	kWh	68.5	45.5	5.4%	
	Upgrading of animal meal	kg	60.8	39.1	4.6%	
	Kiln coal	kg	35.4	12.2	1.4%	
	Transport (rail and road)	tonne.km	58.1	3.6	0.4%	
	Crushed marly limestone	kg	1002.1	2.1	0.2%	
Raw material extraction Cradle-to-gate (entrance)	Upgrading of RDF-fluff (silo)	kg	58.2	1.2	0.1%	
	High grade limestone	kg	501.9	0.9	0.1%	
	Refractory waste	kg	0.5	0.6	0.1%	
	Light fuel oil	kg	0.4	0.3	0.04%	
	Lignite	kg	14.4	0.2	0.02%	
	Upgrading of RDF fluff (kiln)	kg	3.5	0.1	0.01%	
	Upgrading of tires	kg	2.6	0.1	0.01%	
	Upgrading of RDF fluff (agglomerate)	kg	1.4	0.0	0.00%	
	Total raw material extraction phase				106	12%
	Production Gate-to-gate	Calcination of raw materials			541	64%
Combustion of kiln coal				89	11%	
Combustion of RDF fluff (silo)				71	8.0%	
Combustion of lignite				31	4.0%	
Combustion of tires				4.7	0.60%	

Combustion of RDF fluff (agglomerate)	3.2	0.40%
Combustion of RDF fluff (kiln)	2.0	0.20%
Combustion of light fuel oil	1.3	0.20%
Total production phase	744	88%
Total clinker cradle to gate life cycle	850	100%

The results of the LCA study are summarized in Figure 5.

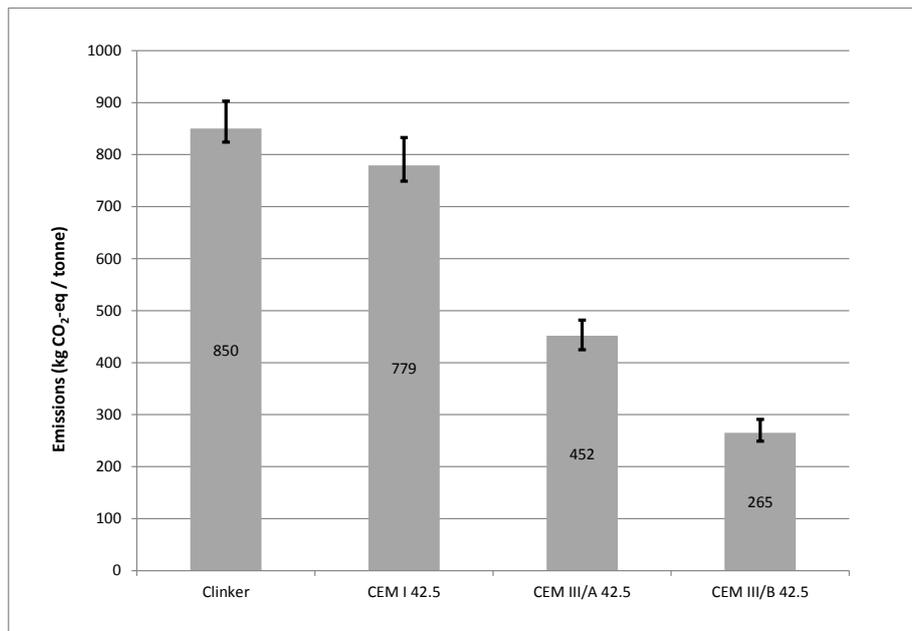


Figure 5. Results of the attributional LCA for Cluster West in 2009.

It is important to remember that these results do not include any allocation of the impact from the iron/steel industry, via the slag (GBFS), to the cement products. This is further dealt with in part III.

Figure 5 also depicts the uncertainty range by applying 95% confidence interval. The uncertainty range in all the studied products was less than 5% of their corresponding emissions. The variations in terms of elementary data are not considered to affect the results and the results are robust.

4 Comparison of production systems using simplified LCA

4.1 Establishment and validation of the simplified LCA model

As described in Methodology, the sensitivity analysis was conducted to quantify the relation between changes of each KPI and the resulting CO₂ emissions. The results are shown in Figure 6, where KPIs with bigger impact have more negative slopes indicating that their improvement contributes more to reduction of the total CO₂ emissions.

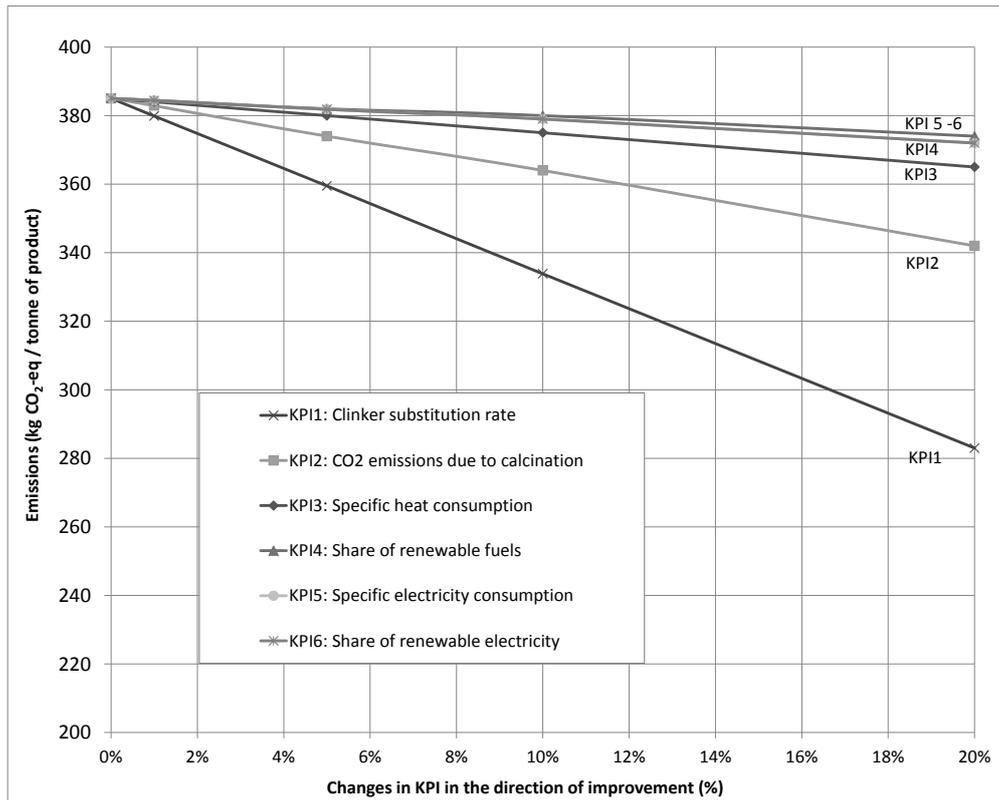


Figure 6. Contribution of different KPIs in improving the CO₂-eq emissions.

For the comparison of different versions of Cluster West, the KPI values were needed, where those for 2009 are presented in Table 3.

Table 3. Values and units for the Key Performance Indicators (KPIs), for the Cluster West clinker and portfolio cement of 2009.

Key Performance Indicator (KPI)	Unit	Cluster West in 2009
KPI ₁ Clinker substitution rate	% mass potfolio cement	60%
KPI ₂ CO ₂ emissions due to calcination	kg CO ₂ -eq/t-clinker	541
KPI ₃ Specific heat consumption	MJ/t-clinker	3915
KPI ₄ Share of renewable fuels	% thermal energy	40%
KPI ₅ Specific electricity consumption	kWh/t	112
KPI ₆ Share of renewable electricity	% electricity	0%

It was then tested if the simplified LCA model created similar results as the original one, as previously described. For this purpose, different products in 2009 were compared, and this showed that the difference between original LCA and simplified model was less than 4%. The simplified LCA model conformed well to the result of the original one. The small difference between the traditional and simplified LCA approach (ranging between -2% to 2%) is acceptable, since the simplified approach is not intended to be used for exact calculations of global warming potential. Its purpose is rather to simplify LCA assessment of complex production systems, based on a few important parameters (the KPIs) instead of a detailed attributional LCA (like step 1). The main aim is to simplify informed decision making, i.e., to be able to draw overall conclusions.

4.2 Simplified LCA assessment for 1997

To assess the historical production system of 1997 (step 3 in Figure 3), the KPIs were altered to reflect that system. For example, the clinker substitution rate, use of alternative fuels and specific electricity consumption were lower. The results are shown in Figure 7, which also includes results for 2009.

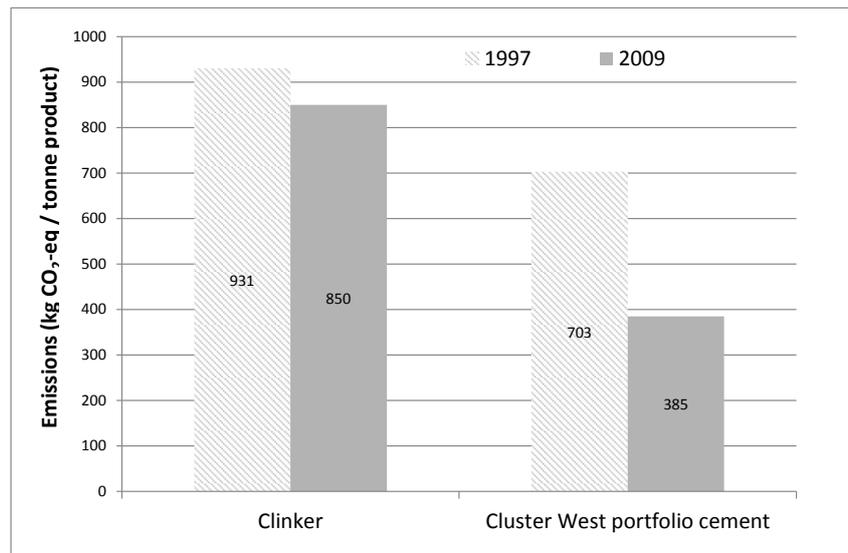


Figure 7. Global warming potential for clinker and portfolio cement (the average product) for Cluster West in 1997 and 2009.

A comparison of the clinker production systems showed important differences. During the 12 years between 1997 and 2009 the global warming potential of the portfolio cement (the average product) has decreased by about 318 kg CO₂/tonne (corresponding to about 45% decrease). Many of the measures behind this development can be characterized as local production efficiency measures at the plant level, for example, improving the kiln so that it can take more diverse types of secondary fuels, thereby replacing fossil fuels. There are however more important initiatives having a wider scope, comprising flows and actors outside the production plants. The most influential improvement measure is, not surprisingly, the increased production of blended cements, where GGBFS to a large extent has substituted clinker.

During the project several future options for development of Cluster West were identified and assessed, and for all of them the simplified LCA model could be applied by translating these changes into updated values for the KPIs (see part II and part III).

5 Concluding discussion

Comparing the results of the attributional LCA, from cradle to gate for 2009, with general results for the cement industry, it can be concluded that CEMEX Cluster West is producing clinker rather efficiently. The performance is good in comparison with average cement production in Europe and many other regions in the World, Japan being one exception (Ammenberg et al., 2011). There are several reasons for this, for example measures within the facilities leading to improved energy efficiency. Another important explanation is the increased share of alternative fuels, of which a part is renewable.

Shifting focus from the production and clinker to the cement products showed that the Cluster West cement product portfolio (a virtual average product) is very favorable from a greenhouse gas emission perspective. This is mainly a consequence of using a high share of clinker substitutes, where granulated blast furnace slag (GBFS) from a steel company is replacing clinker. To illustrate the importance of the production facilities in relation to the type of cement, an interesting conclusion is that the emissions for clinker were reduced about 9% in the period from 1997 to 2009 (to a large extent reflecting changes in technology allowing several types of fuels). In the same period the corresponding figure for the portfolio cement was close to 45%. As expected, less clinker means a lower global warming potential.

To be able to compare different versions of the Cluster West (production systems), a simplified LCA model was developed based on the results of the attributional LCA. This was possible since six key

performance indicators (KPI) to a large extent decided the results. Changes in the types of material and energy inputs, or the technologies used within Cluster West, influence these KPIs which are a robust approximation of the Cluster West production system. For instance, adding a precalciner can decrease KPI₃, or using more alternative fuels with higher renewable fractions can decrease KPI₄. The simplified model made it viable to assess older and future versions of Cluster West. Utilizing information from 1997 the key performance indicators were altered to reflect that production system and therefore the changes from 1997 until 2009 could be analyzed. Similarly, potential improved future versions of Cluster West could also be assessed which is discussed in part III.

In addition to the LCA results, the study illustrated how the results from an attributional LCA study can be utilized to create a much simpler model with reasonable accuracy. The model made it possible to handle dynamics in a complicated production system efficiently. In this case, instead of gathering information about more than 50 parameters, it was enough to monitor six key indicators. The same approach can be used for other cement production systems and it would be interesting to explore the possibilities of using similar approaches in other industrial sectors.

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