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IDENTIFYING ENVIRONMENTAL IMPACTS OF CEMENT PRODUCTION WITH LIFE CYCLE ASSESSMENT: LITERATURE REVIEW

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Abstract

The production of cement is rather complex process which includes a high amount of raw materials (e.g., limestone, marl, clay, and iron ore), heat, electricity and different fuels (petroleum coke, coal, fuel oil, natural gas or different wastes).Because of an important environmental aspect of this sector, numerous studies have done to identify the emissions and energy consumption arising from cement manufacturing. A life cycle assessment (LCA) is one of the valuable methods for assessing the environmental impacts and sustainability of cement production. The aim of this review is critically analysis the LCA studies related to cement production in the literature and discuss the advantages and limitations of LCA methodology.

Key words: *cement, life cycle assessment, environmental impacts*

1. INTRODUCTION

Cement, commonly used construction material, is a fine powder sets after a few hours when mixed with water, and then hardens in a few days into a solid, strong material (CEMBUREAU). Nowadays, the cement production industry is under close investigation because of this sector is thought to represent 5-7% of the total CO_2 anthropogenic emissions. According to the International Energy Agency (IEA)'s report, cement production commonly results in CO_2 emissions average 0.83 ton CO_2/ton cement (Hendriks et. al. 2004). Additionally, it accounts for approximately 12-15 % of the total industrial energy use worldwide (Aranda-Usón et. al. 2012). Huntzinger and Eatmon (2009) have determined that cement production is the third largest source of carbon emission in the USA.

In the circumstances, the ideas of "producer responsibility", "waste minimization" and "zero emission" became crucial (Azapagic 1999). To do these ideas, life cycle assessment (LCA) is one of the methods that a "cradle to grave" systematic approach beginning with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth (EPA, 2006).Sustainability of cement production including potential improvements in energy efficiency, reducing pollutants (especially, CO_2 emissions), waste heat recovery and alternative raw material or fuels usage can be evaluated with LCA. Recently, numerous researchers have used LCA for determining the impacts arising from cement or clinker production (Li et. al., 2015; Huntzinger and Eatmon, 2009; Boesch et. al. 2009; Strazza et. al. 2011). Additionally, a number of researchers have carried out scientific studies about green cement manufacturing (Benhelal et.al. 2012; Amrina and Vilsi 2015; Imbabi et. al., 2012)

This review investigates the applications of LCA related to the cement production. For this purpose, life cycle inventory data and life cycle impact assessment's results on cement process were collected from literature, the results critically assessed and compared with each other.

2. CEMENT PRODUCTION PROCESS

Cement is the essential ingredient of concrete and mortars (CEMBUREAU 2013), and generally produced from the limestone, clay and sand; which provide the four key ingredients required: lime, silica, alumina and iron. Mixing these ingredients and exposing them to intense heat causes chemical reactions that convert the partially molten raw materials into pellets called "clinker."After adding gypsum and other additional materials, the mixture is ground to a fine grey powder called "Portland cement (IEA 2007).

The process of cement production includes three main stages as can be seen from Figure 1:

- Raw material preparation including quarrying raw materials, crushing, prehomogenization and raw meal grinding,
- Clinker burning which includes preheating, precalcining, clinker production in the rotary kiln and cooling and storing,
- Cement preparation which includes blending, cement grinding, storing in the cement silo (IEA-GHG 2008).

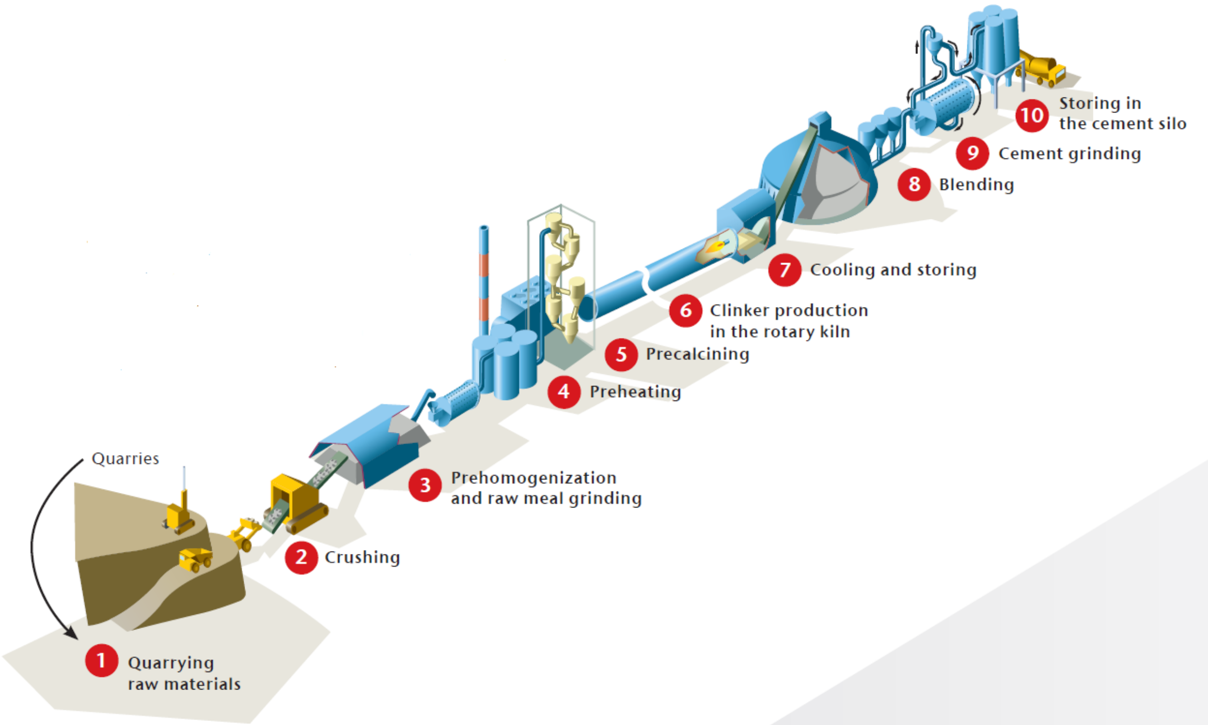

Figure 1. The cement manufacturing process (IEA 2009)

In the first stage, the raw materials are crushed and mixed to produce a homogenized raw mix for rotary kiln. In the second stage of process, the raw mix is fed to the rotary kiln and heated to a temperature of >1400 ^{0}C in a rotary kiln to produce clinker which is the main component of cement (IEA-GH 2008; CEMBUREAU 2013). In the final stage of process, clinker is ground with gypsum and other additives to produce the powder called as “cement” (IEA 2009).

Cements are divided into five main categories according to their contents of clinker substitutes with an allowed range for their chemical composition within the Europe (Table 1). CEM I typically contains 95% clinker. Blended cements can be manufactured with up to 65% of slags or 35% of fly ash and used instead of Ordinary Portland Cement (CEM I) in most applications (Ecofys 2009).

Table 1. Clinker ratios in different cement types (Ecofys 2009).

Cement Type	**Clinker Ratio**
CEM I: Ordinary Portland Cement	95 %
CEM II: Portland Composite Cement	65 – 94 %
CEM III: Blast Furnace Cement	5- 64 %
CEM IV: Pozzolanic Cement	45 – 89 %
CEM V: Composite Cement	20- 64 %

There are two main cement production processes: wet and dry process. The wet process consumes more energy because of the evaporation of the 30% plus slurry water before heating the raw materials to the necessary temperature for calcinations (IEA).

3. LIFE CYCLE ASSESSMENT OF CEMENT

Life cycle assessment of cement is a crucial for determining the environmental impacts from cement production process, developing and preferring the alternative technologies. Due to these reasons, life cycle assessment (LCA) studies are recently performed to determine the environmental impacts and best available technologies to reduce the impacts from cement production (Valderrama et. al. 2012;). Additionally, some researchers investigate the life cycles of different cement types or cement manufacturing types and compared with each other (Feiz et. al. 2014; Boughrara, 2014).

Life cycle assessment consists of four main stages according to the ISO 14040:

- The goal and scope
- The life cycle inventory (LCI): All inputs and outputs of product or process are defined and listed according to the functional unit.
- The life cycle impact assessment (LCIA): Impacts from product or process were determined with different impact assessment methods.
- The life cycle interpretation: The results of LCI or LCIA are reported and discussed within the goal and scope of the study (PE INTERNATIONAL; ISO 14040: 2006).

3.1. Defining of Goal and Scope

In the first stage of LCA, the goal and scope of the study is defined. For this purpose, system boundaries are determined and functional unit is chosen. There are various approaches determining the system boundaries of LCA studies: such as, cradle to grave, cradle to gate, gate to gate… "The cradle to gate" approach contains the impacts of raw material extraction, the production of materials or products until the end-products which is the gate of the factory. On the other hand, the "cradle to grave" approach means for entire life cycle which is includes also use phase and end-of-life phase of the product (Van den Heede and De Belie 2012). However, in some cases, an entire life cycle (cradle to grave) analysis is impossible and the analysis must finish at a "cradle to gate" or "gate to gate" approach for practicability and factuality (Josa et. al. 2004).

LCA studies of cement in literature are generally based on cradle-to-gate approach (as can be seen from Table 2), while the scopes of cradle-to-gate studies are various. Figure 2 shows that an example of the cradle-to-gate LCA of cement production (EPA, 1994). As can be seen from the Figure 2, system boundaries of conventional cement production are includes extraction of raw materials (quarrying), preparation of raw materials (crushing, homogenization and mixing), clinker production in rotary kiln, cement production and packaging/handling/shipping of the end product.

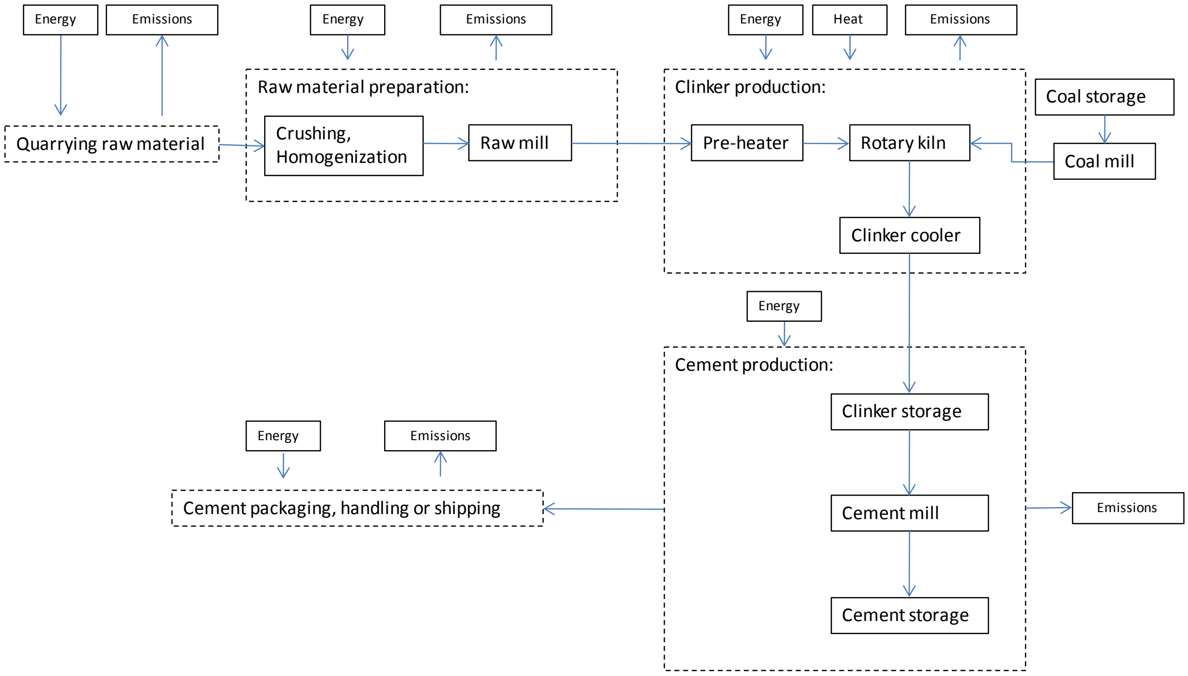

Figure 2: Material flow and system boundaries of cradle-to-gate LCA of cement production (adapted from Huntzinger and Eatmon, 2009).

Table 2 presents the main production processes of cement and the scientific LCA studies performed with in this context. As can be seen from the Table 2, the system boundaries of the cradle-to-gate LCA studies are vary by the aim of the study. The common characteristic of the studies presented in Table 1 is the clinker production process which is the most energy intensive and pollutant generated process of cement production. Extraction of raw materials (quarrying) is excluded in some studies (Li et. al. 2004; Boesch and Hellweg 2010; Josa et. al. 2004). The researchers define several functional units according to the end product of their scientific studies. The functional unit was defined as 1 kg/t cement in some of the studies (Feiz et. al. 2014; Boesch and Hellweg 2010; Chen et. al.2010;Huntzinger and Eatmon 2009;Josa et. al. 2004). In some of the studies (Li et. al. 2014; Garcia-Gusano et. al. 2015), 1 t clinker and 1 t cement were chosen as functional unit at the same time, because the life cycle of different cements types (such as CEM I, CEM II, CEM III….) was assessed.

Table 2. Differences of cradle-to-gate approaches of cement production LCA studies

Reference	Functional Unit	Raw Material Extraction (Quarrying)	Raw Material Preparation (Grinding and mixing)	Fuel Preparation	Clinker Production	Cement Production	Transportation of end product to first consumer
Feiz et. al. 2014	1 t cement	x	x		x	x	x
Li et. al. 2014	1 t P.O. cement 1 t clinker		x		x	x	
Boesch and Hellweg 2010	1 t cement		x	x	x	x	
Garcia-Gusano et. al. 2015	1 t clinker 1t cement	x	x	x	x	x	
Aranda-Uson et. al. 2012	1 kg clinker	x	x		x		
Valderrama et. al. 2012	1 kg clinker	x	x	x	x		
Chen et. al. 2010	1 kg CEM I	x	x	x	x	x	
Huntzinger and Eatmon 2009	20 bags of P.O. cement	x	x		x	x	x
Josa et. al. 2004	1 kg cement				x	x	

Transportation is also an important data in LCA studies. In order to attain the variable results, it is crucial that more specific data is obtained related to transportation distance of raw materials or end products (Nisbet et. al. 2002). As seen from the Table 2, while many researchers include the transportation of raw material in their LCA studies, the others includes the process of transportation of end product to first consumer (Feiz et. al. 2014; Huntzinger and Eatmon 2009).

3.2. Life Cycle Inventory Analysis (LCI)

Inventory analysis can be defined as the most critical stage of life cycle assessment approach because of the data availability and quality. The needed information about inputs and outputs can be obtained from the cement production industry, environmental production declarations (EPDs) or LCA databases (such as Ecoinvent) (Van den Heede and De Belie 2012). In Figure 2, the simple flow chart including fundamental inputs and outputs of cement production is presented. LCI studies about cement production include different inputs and outputs according to the scope of the study. Some scientific studies include the quarrying activities (drilling and blasting), but some of them include only transportation of raw materials.

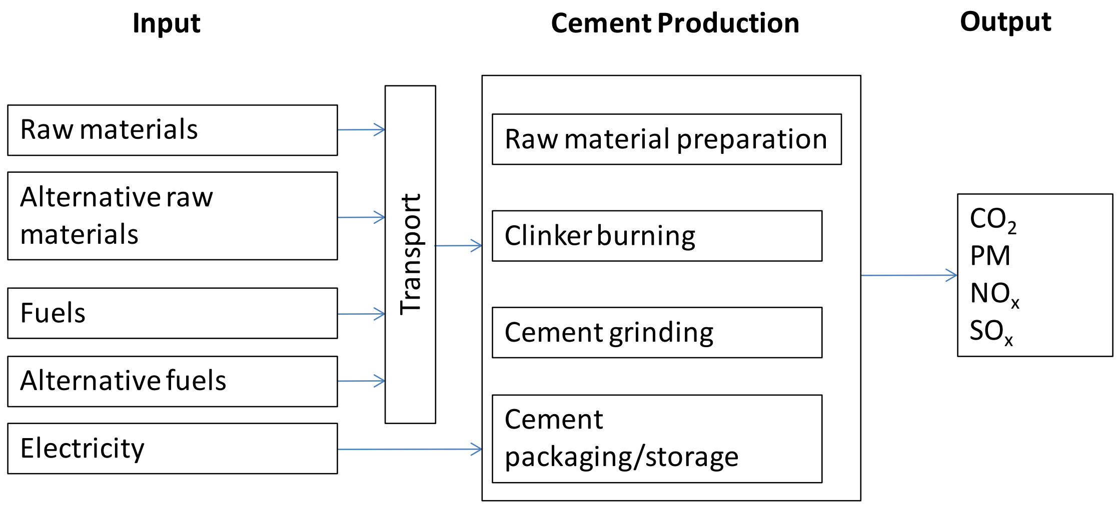

Figure 2. The overall input and output of cement production

The input and output data of cement production obtained from literature are shown in Table 3. Life cycle inventory data including clinker or cement composition, energy consumption, transports, raw materials, fuels and emissions were usually provided by producer and normalized for the selected functional unit in presented scientific studies (Table 3). The amounts of raw materials, energy consumed and transport data are considered as the input. The raw material consumed to product 1 t clinker is range from 1.50 – 1.70 ton (Garcia-Gusano et. a. 2015, Aranda-Usón et. al. 2012; Valderrama et. al. 2012). Approximately 1.6 ton raw material is consumed per ton clinker in cement production sector (European Comission 2012; Gabel et. al. 2005). Recently, alternative raw materials are used for sustainable cement production. Slags, fly ash, mining wastes, pyrite ashes, aluminum oxides, ceramic wastes (Puertaset. Al. 2008; Li et. al.2014; Chen et.al.2014) and iron ore wastes are used as alternative raw materials in order to product cement in scientific studies (Garcia-Gusano et. al. 2015; Amaia et. al. 2014). Fly ashes and various industrial sludges can be substituted for ingredients such as Ca, Fe, Al and Si (Petavratrzi and Barton 2007).

The energy consumed is divided into thermal energy and electricity (Josa et. al. 2004). Electricity used in the cement production process consists of prehomogenization, crushing and grinding, running the machines (such as fans, kiln drives), conveying the materials to preheaters, or cooling system. Mills and the exhaust fans are the main users of electricity and together account for more than 80% of electrical energy usage (European Comission 2012). In some cement production plants which have quarries on-site, both trucks and conveyors are used to move raw materials from quarries to process. Additionally, the energy consumption for other conveying and auxiliaries and non-productional uses (such as lighting, office equipment...) must be considered as input (Galitsky et. al. 2008). Thermal energy is mainly consumed in clinker kiln (Josa et. al. 2004). Fossil fuels used for pyroprocessing compose the majority of fuel consumption (Petek Gürsel et. al. 2014). A wide range of fossil fuels are used, such as petroleum coke, lignite, natural gas and fuel oil. Additionally, large quantities of alternative fuels (waste derived fuels, tires, solid and liquid wastes, dewatered sludges and biomass fuels) are also used in the cement industry (European Comission 2012; Worrell and Galitsky 2008; Hong and Li2011; Chen et. al. 2010). 3000-6000 MJ energy per ton of clinker and 90-150 kWh electricity per ton of cement are generally consumed depending on kiln system technology and on raw materials and fuel properties. In Europe, the average heat requirement of 3600 MJ per ton of clinker was predicted from the operating kiln systems with 3500 MJ/ton clinker for dry and semidry kilns (European Comission 2012; Boesch and Hellweg 2010). Li et. al. (2014) measured the electricity consumption as 71 kWh/t P.O cement. The researchers suggest that the consumption of electricity in cement grinding process change with grindability of clinker, gypsum and different admixtures (Li et. al. 2014). In Turkey, 3350±210 MJ/tonne.clinker energy and 110±5 kWh/ton cement electricity are consumed in cement production (Petek Gürsel and Meral 2012).

While some studies assessed the life cycle of only Portland ordinary cement, numerous LCA studies were practiced related to the life cycle assessment of different cement types and compared with each other (Feiz et. al. 2014; Garcia-Gusano et. al. 2015; Josa et. al 2004).In addition to the clinker composition, the cement grinding process comprises of the different constituents (such as gypsum, blast furnace slag, pozzolana, fly ash, limestone…etc) according to the each cement type (Garcia-Gusano et. al. 2015). Feizet. al. (2014)assessed the global warming potential (GWP) of three different cement types (CEM I 42.5, CEM III/A 42.5 and CEM III/B 42.5) with using the functional unit of 1 tonne cement manufactured. GWPs were found as 779 kg CO_2-eq/t; 452 kg CO_2-eq/t and 265 kg CO_2-eq/t for CEM I 42.5, CEM III/A 42.5 and CEM III/B 42.5; respectively. Josa et. al. (2004) also found the CO_2 emission for CEM I approximately 800 kg/t cement in accordance with Feizet. al. (2014). Garcia-Gusano et. al. (2010) also investigated the environmental impacts of different cement types (CEM I, CEM II, CEM III, CEM IV, CEM V and other cements) by LCA. Garcia-Gusano observed that Portland cement (CEM I) contributes with up to 30% to each environmental impact assessed. Additionally, CEM II (fly-ashed) and CEM II (calcareous) and CEM II (composite) also have significant effects on all impact categories.

The main outputs from the cement production are emissions to air from the kiln system. These can be defined as combustion gases and derive from the physico-chemical reactions involving the raw materials and the combustion of fuels. The main constituents of the outputs of kiln system are defined as PM, CO_2, NOx and SOx as shown from Figure 2. The amounts of CO_2 are range from 650-920 kg of CO_2 per tonne cement, based on properties of cement plant. The average is approximately 830 kg of CO_2 per tonne of cement at worldwide (Moya et. al. 2010). Noise emissions also arise during the manufacture of cement. In addition to PM, CO_2, NOx and SOx emissions;, CO, TOC/VOC, HF, HCl, PCDD/F and some metals (Cd, Hg, Tl, As, Sb, Pb, Cr, Co, Cu, Mn, Ni, V) are also emitted from cement kilns (European Commission 2012). The particulate matter emissions are also arising from quarrying, crushing and grinding of raw materials, transport of raw materials with conveyors or lorries, storage of raw material, fuel and cement, and cement loading.

Table 3. The LCI of clinker and cement production obtained from scientific studies.

Input/Output	Hong and Lee 2011	Josa et. al. 2004	Chen et. al. 2014	Chen et. al.2010	Li et. al. 2014	Amaia et. al. 2014	Valderamma et. al. 2012	Aranda-Uson et. al. 2012	Garcia Gusano et. al. 2015
Functional Unit	kg/t cement	kg/kg P.O cement	kg/t P.O. cement	kg/kg P.O cement	kg/t P.O cement	kg/t clinker	kg/kg clinker	kg/kg clinker	t/ t clinker
Raw Materials:									
Byproduct: Clinker		0.95				733.3			
Limestone	1160		1050	1.22	1150		1.181	1.18	1.12
Sand	6.10		54.81		40	4.7	0.069	0.07	0.0273
Clay		0.057		0.31			0.346	0.35	0.0797
Marl		1.610				254.6			0.277
Kaolin									0.00528
Bauxite									0.00261
Iron ore /Iron oxides	1.70	0.019			7.5		0.013	0.01	0.00833
Gypsum	50	0.050	50.51	0.01	50				
Alternative Raw Materials:									
Aluminium oxide, waste									0.000398
Blast furnace slag		0.109							0.00316
Fly ashes		0.09	241.39		155-200				0.00298
Iron ore, waste						7.4			0.00476
Mining wastes									0.00161
Water (m^3)	180[a]		360[a]	0.2E-03	0.165		5.56E-04		0.00162
Energy:									
Electricity (kWh)	103.39		81.93	13.5E-02	71	29.08	7.57E-02	0.0757[a]	92
Pet coke						96.45	1.06E-01	0.106	2.89[b]
Bituminous coal /Hard coal	94.69		101.94	9.8E-03			5.61E-09	5.61E-09	0.0437[b]
Heavy fuel oil				1.6E-02		1.73	1.61E-09	1.61E-09	0.0341[b]
Natural gas									0.00436[b]
Diesel							9.12E-07		0.000572[b]

Table 3. The LCI of clinker and cement production obtained from scientific studies (continuing).

Alternative Fuels:									
Dewatered sludge	83.55								
Waste				1.20E-03 [b]					
Waste tyres						17.44			0.172 [b]
Munipicial sewage sludge									0.0301 [b]
Munipicial solid waste						1.065			
Refused derived fuel									0.0973 [b]
Transport (kgkm):									
Barge							1008	1010	
Truck				56.86				17.6	
Lorry							17.62		22090
Boat				97.7					
Train				1.22					
Conveyor belt									2000
Outputs:									
Emissions:						1.14E+00		1.48E-04	
CO	0.15	0.355	620	6.9E-01	605	7.35E+02	8.56E-01	3.71E-01	5.28E-01
CO_2	760					1.51E-02			
CO_2, biogenic		0.01	6.5E-02	4.9E-04	0.095	6.18E-02	3.00E-05		1.04E-05
PM / Dust	3.6E-02	0.00096	1.9E-01	1.2E-03	0.68-1.65	1.04E+00	1.55E-03	1.60E-03	
NO_x	9.3E-01	0.00043	2.3E-02	8.2E-04	0.036-0.113	9.84E-02	5.06E-04	1.60E-03	
SO_2	9.0E-02			4.5E-05	0.3047 [c]	1.37E-02		5.54E-06	
NMVOC						9.41E-03			
VOC				3.3E-06		4.53E-05			
Benzene				7.2E-04		4.83E-03			
Ammonia	1.2E-02 [c]				0.00332 [c]	9.60E-13			
Dioksin (PCDD/Fs)						8.88E-06		5.54E-06	
CH_4				3.2E-08	7.62-27.4 [d]	1.20E-08		5.17E-05	
As	5.09E-05 [c]					3.00E-09			
Cd	7.92E-04 [c]			1.4E-08		4,00E-09			
Cr	5.28E-03 [c]			2.8E-07	1.14-1.52 [d]	1.72E-05		1.35E-12	
Cu	3.02E-03 [c]			3.4E-08	0.572-0.91 [d]	3.30E-08		4.18E-12	
Hg	2.40E-01 [c]			2.8E-07		1.09E-05			
Mn				1.6E-07		2.18E-06		5.62E-10	
Ni	1.00E-02 [c]			9.8E-07	1.60-13.95 [d]	7.61E-05		1.12E-11	
Zn	1.00E-02 [c]			2.2E-07		9.68E-06			

[a]: kg ; [b]: GJ; [c]: g; [d]: mg

3.3. Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) can be subdivided into four main stages, which are:classification, characterization, normalization and weighing. In the first stage, each environmental aspect determined in LCI is associated with the impact category; for instance, CO_2 is associated with the greenhouse effect. In the characterization stage, the relative effects of all the environmental aspects associated with each of the different impact categories are compared to one another; for instance, the potential impact of carbon dioxide and methane on global warming is modeled. In the normalization, the results of each impact category are divided by a reference figure. In the weighing stage, the most important potential impacts are emphasized (Josa et. al. 2007; EPA).

Selection of impact categories, category indicators and characterization models is important to document the subjective choices that are made in the selection. In practice this selection is implied by choice of impact assessment methods (Carlson et. al. 2003).The following LCIA methods are implemented in the ecoinvent data v2.0: CML 2001, Cumulative energy demand, Cumulative exergy demand, Eco-indicator 99, Ecological footprint, Ecological scarcity 1997, Ecosystem damage potential (EDP, EDIP'97 and 2003), IMPACT 2002+, IPCC 2001 (climate change), TRACI (Althaus et. al. 2010). Two main methods are used for impact assessment in the literature: Problem-oriented methods (CML 2002, EDIP…etc) and damage-oriented (Eco-indicator 99, EPS, IMPACT 2002+…etc) methods (Van De Heede and De Belie 2012; Josa et. al. 2007; Chen et. al. 2010). A problem-oriented approaches translate impacts into mid-point impacts such as climate change, acidification, human toxicity, etc; whereasa damage-oriented approaches translate environmental impacts into end-point impacts such as human health, natural environment, and natural resources (PE INTERNATIONAL).

In Table 4 and Table 5, problem-oriented impact categories and damage-oriented impact categories are presented according to the two different selected LCIA methods: Eco-indicator 99 and CML 2001. In addition to CML 2001 method, IPCC GWP method is also a problem-oriented method because it only quantifies GHG emissions (in kilograms CO_2 equivalents) and not the resulting climate change related damage (in disability adjusted life years - DALY). When the main aim of the scientific study is determine the only greenhouse gases (GHG), IPCC GWP method can be used (Van De Heede and De Belie 2012).

Table 4. The relation between LCI data, impacts and damage categories of Eco-indicator method (Goedkoop and Renilde 2000)

LCI data	**Impact (Mid-point)**	**Scale**		**Damage category (End-points)**
Extraction of minerals and fossil fuels	Surplus energy for future extraction	Global Regional Local		Damage to mineral and fossil resources
Land use: occupation and transformation	Effect on vascular plant species	Regional Local		Damage to ecosystem quality
NO_x, SO_x, NH_3	Asidification, Eutrophication	Regional Local		
Pesticides Heavy metals	Ecotoxicity: Toxic stress (PAF)*	Local		
CO_2, HCFC	Climate change	Global		Damage to human health
HCFC	Ozone layer depletion	Global		
Nuclides (Bq)	Ionize radiation			
NO_x, SO_x, SPM, VOC_s	Respiratory effects	Global Regional Local		
Heavy metals, PAHs	Carcinogenesis	Global Regional Local		

*PAF: Potentially Affected Fraction

Table 5. Problem oriented impact categories according to CML 2001 method (Althaus et. al. 2010).

Impact categories	**Unit**
acidification potential	kg SO_2-Eq
climate change	kg CO_2-Eq
eutrophication potential	kg PO_4-Eq
freshwater aquatic ecotoxicity	kg 1,4-DCB-Eq
human toxicity	kg 1,4-DCB-Eq
land use	m2a
marine aquatic ecotoxicity	kg 1,4-DCB-Eq
photochemical oxidation (summer smog)	kg formed ozone
resources	kg antimony-Eq
stratospheric ozone depletion	kg CFC-11-Eq
terrestrial ecotoxicity	kg 1,4-DCB-Eq
freshwater sediment ecotoxicity	kg 1,4-DCB-Eq
malodours air	m3 air
marine sediment ecotoxicity	kg 1,4-DCB-Eq
ionising radiation	DALYs

LCA impacts and methods considered in different scientific studies obtained from literature are summarized in Table 6. Some of the studies summarized in Table 6 carried out impact assessment according to the cement production stage (calcination, transport, mining, clinker production, packaging..etc) (Garcia-Gusano et. al. 2015; Amaia et. al. 2014), while some of them identified different scenarios (sewage sludge usage as alternative raw material or fuel) in cement production process (Hong and Li 2011;Aranda-Uson et. al. 2012) and investigated the differences comparatively. In generally, energy usage and emissions arising from clinker process have an important role on all of the environmental impacts (Hong and Li 2011). It was found that clinker is responsible of the dominant impact (approximately 80%) in all of the mid-point impacts, except for terrestrial ecotoxicity in one of the LCA studies (Amaia et. al. 2014). Chen et. al. (2014) found that energy production process made the largest contribution to the non-carcinogens respiratory organics and non-renewable energy categories, while transport process made largest contribution to the carcinogens, ionizing radiation and ozone layer depletion impact categories.

Hong and Li (2011) assessed the environmental effect of sewage sludge usage as secondary raw material in cement production by selecting two scenarios: cement production without sludge and cement production with sludge. The result of the LCA study showed that sewage sludge usage as secondary raw material had small effect to reducing the environmental impacts, except for the respiratory inorganic. In this category, cement with sludge has slightly low environmental impact because of the low NO_x emissions. In another scientific study, environmental analysis of sewage sludge usage as secondary fuel in cement manufacturing was investigated and four scenarios were selected. LCIA was carried out based on mid-point and end-point approaches. When the fossil fuel (pet coke) is replaced by alternative fuel (sewage sludge) nearly all mid-point impact categories improved; except for human toxicity, terrestrial ecotoxicity and marine ecotoxicity. The main reason of this circumstance was explained as high content of heavy metals of selected sewage sludge (Aranda-Uson et. al 2012). Garcia-Gusano et. al. (2015) identified five scenarios including thermal efficiency, electrical efficiency, material substitution, fossil fuel substitution and ideal (all improvements together) categories to implementation of the best available technologies and life cycle impacts were assessed by mid-point approach for each scenario. Garcia-Gusano et. al. (2015) determined that changing the primary materials by secondary materials (such as fly ashes, blast furnace slag) leads to 10-13% reductions in each impact category. When alternative fuels were used instead of fossil fuels, acidification and photochemical ozone formation impact categories decreased to 37% and 33%, respectively. Strazza et. al. (2011) also investigated the environmental performance of active cement plant, which is used recovered plastics as alternative fuel in cement manufacturing, and the alternative fuels usage is determined as an ideal method to reducing environmental impacts.

The impacts based on the some mid-point impact categories such as respiratory inorganic, terrestrial ecotoxicity; global warming and non-renewable energy have an important contribution in cement production (Hong and Li 2011; Chen et. al. 2014). The relevant gas emissions related to the greenhouse effect in the life-cycle inventory (LCI) analyzed are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Valderrama et. al 2012; Josa et. al. 2007). However, major sources of GHG in cement manufacturing are CO2 arising from calcination process and fuel combustion (Boesch and Hellweg, 2010). NO_x, SO_2 and particles contribute the respiratory inorganic (Hong and Li 2011). Coal and oil, which are used to generate energy, are the dominant materials in the non-renewable energy category (Chen et. al. 2014). Human toxicity category is impressed by toxic organic compounds, heavy metals and NO_x emissions; whereas the cumulative energy demand is dominated by fossil fuel consumption in the rotary kiln (Boesch and Hellweg, 2010).

Boesch and Hellweg (2010) also assessed the life cycle impacts (climate change, CExD, acidification, eutrophication and human toxicity) of different cement types in Europe: CEM I, CEM II, CEM III, CEM IV and CEM V. Climate change impact category found as 903 kg CO_2-eq for CEM I, 742 kg CO_2-eq for CEM II, 354 kg CO_2-eq for CEM III, 628 kg CO_2-eq for CEM IV and 412 kg CO_2-eq for CEM V. The highest impacts were assessed for production of CEM I cement in all of the impact categories. CO_2 emissions from cement manufacturing are impressed by energy efficiency, the fuel mix used to obtain the needed heat and the amount of carbonate materials used in clinker production in addition to clinker ratio of cement (Boesch and Hellweg, 2010).

Table 6. LCIA studies obtained from literature.

Scientific Study/ Impact Category	Boesch and Hellweg (2010)	Chen et. al. 2014	Aranda-Uson et. al. 2012	Hong et.al. 2011	Garcia-Gusano Et. al. 2015	Amaia et. al. 2014	Valderrama et. al. 2012
Global warming potential	*	*	*	*	*	*	*
Acidification	*	*	*	*	*	*	*
Eutrophication	*	*	*	*	*	*	*
Abiotic Depletion					*	*	*
Ozone layer depletion		*	*	*	*	*	*
Aquatic ecotoxicity		*	*	*	*	*	*
Terrestrial ecotoxicity		*	*	*	*	*	
Photochemical oxidation			*		*	*	*
Cumulative Exergy Demand	*						*
Cumulative Energy Demand							
Human toxicity	*		*	*	*	*	
Respiratory effects		*		*	*		
Ionizing radiation		*	*	*	*		
Particulate matter formation			*				
Land use		*	*	*	*		
Non-renewable energy		*		*			
Mineral extraction		*		*			
Resource depletion			*				
LCIA method used	IPCC (100y) CML 2001	IMPACT 2002+	RECIPE	IMPACT 2002+	ILCD 2011	CML-IA	IPCC(100y) CML 2000

End-point impact categories such as climate change, human health, ecosystem quality,and resource depletion were assessed in numerous LCIA studies in literature. According to the Chen et. al. 2014, energy generation had an important contribution in the resource depletion and direct emission made a dominant contribution to climate change.

4. CONCLUSIONS

Life cycle assessment is a beneficial tool in order to identify the environmental aspects and assess the environmental impacts from cement manufacturing process. Additionally, it is an important for decision-makers to enhance the best available technologies in manufacturing process. The choice of functional unit and determination of scope is significant stage of LCA studies in terms of the presentation of results compatibly in interpretation stage. The scope of LCA studies are classified as gate-to-gate, cradle-to-gate and cradle-to-grave. Due to a cradle-to-grave analysis is not favorable in some cases for cement manufacturing, the scope of LCA studies are chosen as “cradle-to-gate” or “gate-to-gate” for reliability of scientific study.

Inventory analysis can be defined as the most important stage of LCA studies because the inventory data used directly influence the LCA results. Despite the numerous LCI and LCA studies have performed related to the cement production, this is still limited research area from the point of different cement types, environmental impacts and best available technologies. Life cycle assessment of ordinary Portland cement has investigated by many researchers. But in a few study, the life cycle of different cement types (such as, CEM II, CEM II, CEM IV and CEM V) have assessed comparatively. Environmental impacts arising from cement production have assessed based on the GHG and criteria air pollutants in lots of studies. The outputs such as, hazardous air pollutants (PAHs, PCDD/Fs, HCl…etc) and toxic heavy metal emissions (As, Cd, Hg, Cr,…etc) have neglected in numerous studies. However, it is significant to include these data in inventory analysis in order to assess the all environmental impacts from cement manufacturing process using alternative raw material or alternative fuel (sewage sludge, fly ashes,…etc).Additionally, wastewater and solid wastes should be also considered in inventory database.

The usage of alternative raw materials and fuels in cement manufacturing process has increased recently to ensure the waste minimization, resource conservation and environmental benefits. For this purpose, the further investigation is needed for alternative fuel/raw material usage in cement production and determination of best available technologies in manufacturing process. And the life cycle inventory inputs and outputs should be enhanced within this context.

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