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Emissions from Portland Cement Production Using Life Cycle Assessment Inventory and Method

Saeed Morsali

Gazi University, Faculty of Applied Science, Department of Environmental Science, Ankara, Turkey

Email address:
morsali.saeed@gmail.com

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Abstract: Cement production is one of the vastest industries all over the world which release many kinds of substances into air, soil and water that cause significant effects on human health and global warming, this industry uses many resource and energy to produce one of the most useful products in the construction sector. In this study, we used Simapro and LCA method to analysis the cement lifecycle impacts on human health, ecosystem quality and resource depletion. From the analysis released emissions are obtained per separate impact category.

Keywords: Portland Cement Production, Life Cycle Assessment (LCA), Cement Production Emissions, Simapro, Eco-indicator 99

1. Introduction

With the increasing danger of catastrophic global environmental change due to environmental mismanagement during the last decades, it is necessary to take action not only in resources using but also in industry and production sector. In recent years many sectors try to follow various ideas and initiatives such as green growth, green economy, green transformation, green structural transformation, sustainable transformation, and green industrial policy because growing environmental issues persuade many countries and sectors to reduce environmental loads from both production and application of materials. Green transformation refers to processes within industries and/or companies that lead to reduced environmental change impact [1]. One of the most widely used methods for assessing environmental loads is LCA methods which have a cradle to grave perspective to assess all aspects of a product or service. An LCA is a measure of the environmental impacts of a product, process or service during the course of its useful life. [2].

Life Cycle Assessment (LCA) studies indicate the synergistic products are favorable from an environmental perspective [3]. 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). Portland cement is a hydraulic cement composed primarily of hydraulic calcium silicates. Hydraulic cements harden by reacting chemically with water. During this reaction, cement combines with water to form a stonelike mass, called paste. When the paste (cement and water) is added to aggregates (sand and gravel, crushed stone, or other granular materials) it binds the aggregates together to form concrete, the most widely used construction material [4].

Because of an important environmental aspect of this sector, numerous studies have done to identify the emissions and energy consumption arising from cement manufacturing [5]. I n this study we considered the most important waterborne and airborne emissions as well as emissions to soil from an extraction of raw material until the end of cement life using commercial inventory database.

The cement industry is one of the major contributors for greenhouse gases (GHG) emissions, specifically CO_2 emissions. This is due to the calcinations of raw materials for the production of cement and burning fuels needed to maintain high temperatures in a kiln sector in the world released 2.37 Gt air pollutants to the environment. Regarding CO_2 emissions, the global emissions of CO_2 reached approximately 28.3 Gt in 2005, of which the cement industry generated approximately 1.8 Gt CO_2, indicating that the cement industry contributed approximately 6% of the total global CO_2 emissions. Some measures have been considered in order to reduce the CO_2 emissions of the cement industry, e.g., use of carbide slag as an alternative raw material for low carbon cement may lead to a drastic reduction. The low carbon substitutions provide significant opportunities for symbiotically utilizing large quantities of by-products of other industrial processes [6]. However, indirect energy use and extra emissions (including fly ash) of alternatives have not yet been fully considered during the CO_2 accounting [6].

In this study, we aim to assess Portland cement cradle to grave impacts on human health, ecosystem quality and resources. Obtaining most critical processes which have more impacts to the environment, released substances during cement life cycle with their amount. Determining critical processes helps to manager and employers as well as scientists to focus on these processes in order to reduce the main and highest impact causes.

2. Methodology

The analysis of the product life cycle evaluates the interaction between the “product life”, from raw material extraction to final product disposal, and the environment, trying to characterize the impacts imposed to the environment. In an LCA study on a product, process or service, all extractions of resources and emissions from/to the environment are determined, when possible, in quantitative values throughout the life cycle from “cradle to grave”. The LCA analysis has to be based on these data and evaluates the potential impacts on natural resources, environment and human health [7]. One of the most important parts of a life cycle assessment tool is the methodology. In this study for validating the data and analysis, a commercial version of Simapro7.1 is used, since Simapro uses different kind of methods for analysis the used method for this paper is Eco-Indicator 99 method which has three main impact category; human health, ecosystem quality and resources.

2.1. Inventory Data

Inventory data for this study is taken from Simapro database inventory table, for Portland cement production the system model basic materials describes the production of different materials that are used in the life cycle of western Europe energy system. The materials considered are mineralogical materials (sand, gravel, cement, concrete, float glass, mineral wool, lime, limestone, gypsum, clay, barite, bentonite, ceramics, and molecular sieve), inorganic chemicals (chlorine, caustic soda, nitric acid, phosphoric acid, ammonia, iron sulfate, sodium carbonate, hydrofluoric acid, hydrochloric acid, sulfuric acid, secondary sulfur, urea), organic chemical, metals, plastics, biogenic materials. The inventory tables include resource extraction, refining and production of bulk intermediate products. These data is taken from Portland cement production from clinker and calcium sulfate. The energy values stem from various publications.

2.2. System Boundaries

The systems are divided into subsystems interconnected by flows of materials, energy and environmental discharges. In this study Portland cement production inventory analysis includes extraction, transportation, production stages, land uses for extraction step, only production waste are considered, materiel production assumed to happen in the nineties even if the material is used in the early twentieth, energy consumption, waterborne and airborne emissions, emissions to the soil, transportation from factory to the markets, raw material production, all these steps are shown in figure 1 as system boundaries.

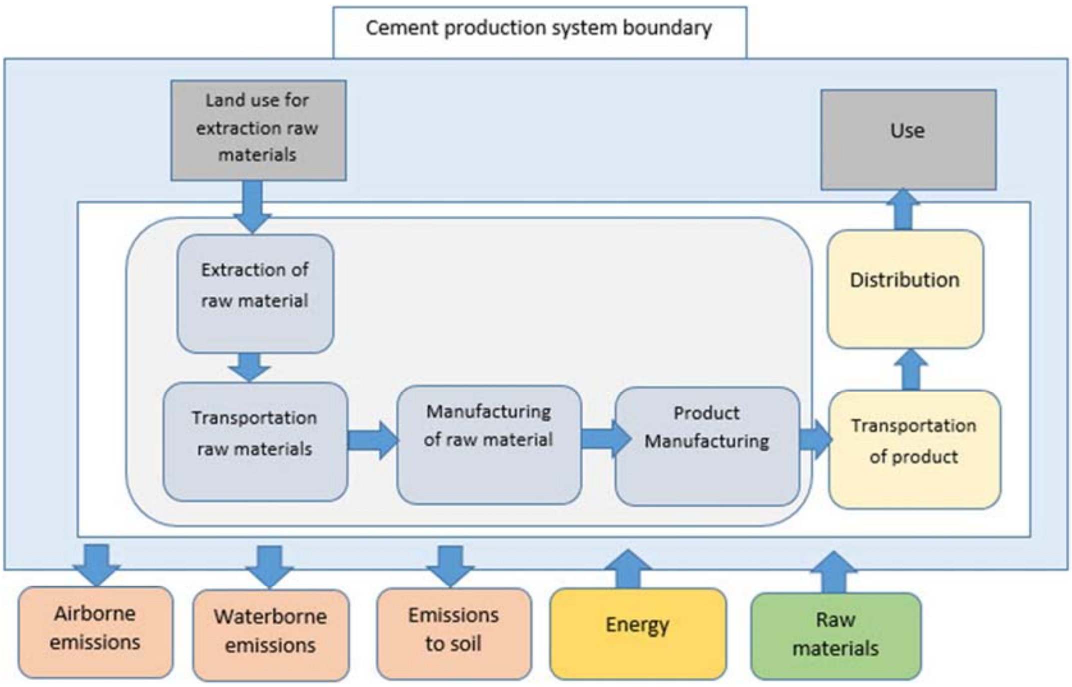


Figure 1. *System boundary for Portland cement production.*

2.3. Impact Assessment of Portland Cement Production

As it mentioned Eco-Indicator 99 uses three main impact category which every impact includes specific impacts as they are listed below;

- Human health;
  (1) Carcinogens: Carcinogenic affects due to emissions of carcinogenic substances to air, water and soil. Damage is expressed in Disability adjusted Life Years (DALY) / kg emission.
  (2) Respiratory organics: Respiratory effects resulting from summer smog, due to emissions of organic substances to air, causing respiratory effects. Damage is expressed in Disability adjusted Life Years (DALY) / kg emission.
  (3) Respiratory inorganics: Respiratory effects resulting from winter smog caused by emissions of dust, sulphur and nitrogen oxides to air. Damage is expressed in Disability adjusted Life Years (DALY) / kg emission.
  (4) Climate change Damage: expressed in DALY/kg emission, resulting from an increase of diseases and death caused by climate change.
  (5) Radiation Damage: expressed in DALY/kg emission, resulting from radioactive radiation.
  (6) Ozone layer Damage: expressed in DALY/kg emission, due to increased UV radiation as a result of emission of ozone depleting substances to air.
- Ecosystem quality;
  (1) Ecotoxicity Damage to ecosystem quality: as a result of emission of ecotoxic substances to air, water and soil. Damage is expressed in Potentially Affected Fraction (PAF)*m2 *year/kg emission.
  (2) Acidification/ Eutrophication Damage to ecosystem quality: as a result of emission of acidifying substances to air. Damage is expressed in Potentially Disappeared Fraction (PDF)* m2 *year/kg emission.
  (3) Land use: Damage as a result of either conversion of land or occupation of land. Damage is expressed in Potentially Disappeared Fraction (PDF)* m2 *year/ m2 or m2a.

Mankind will always extract the best resources first, leaving the lower quality resources for future extraction. The damage of resources will be experienced by future generations, as they will have to use more effort to extract remaining resources. This extra effort is expressed as “surplus energy”.

- Resources;
  (1) Minerals: Surplus energy per kg mineral or ore, as a result of decreasing ore grades.
  (2) Fossil fuels: Surplus energy per extracted MJ, kg or m3 fossil fuel, as a result of lower quality resources.

In weighting step, Simapro uses Pt unit to show these impacts. The Pt unit used in eco indicator method defined as a dimensionless value. The value of 1 Pt means one thousandth of the yearly environmental load of one average European inhabitant. In this paper, all the analysis have been done for 1 kg Portland cement production. To compare human health, resources and ecosystem quality impacts with the same unit we used weighting option in Simapro which is shown as figure 2.

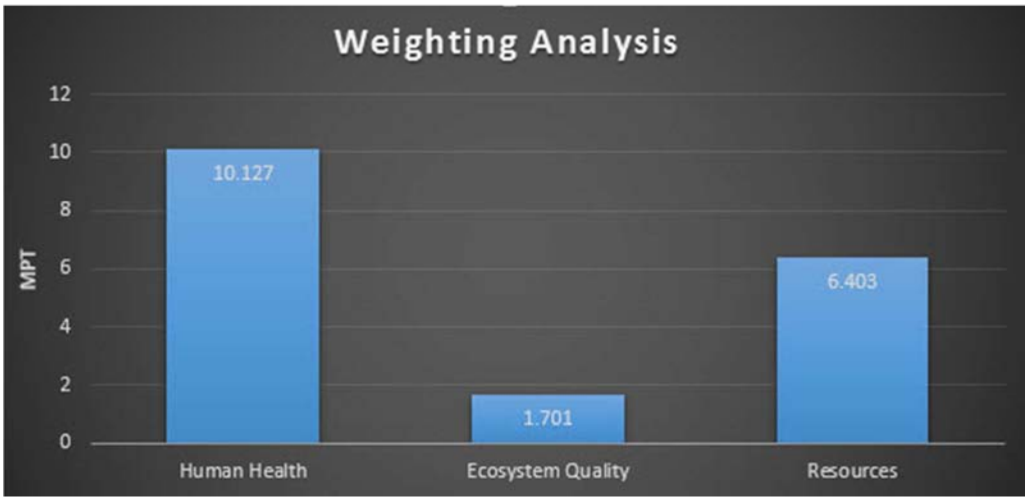


Figure 2. *Weighting of Portland cement production.*

The figure shows a compared graph between three main impacts category with Pt unit. As figure 2 shows the most damage occurs in human health category during cement life cycle.

As mentioned before each main impact category include subcategories that figure 3 shows these subcategories. Like figure 2, to compare these subcategories we used weighting option since it has the same unit for all subcategories.

Figure 3 shows weighting of all impacts for cement life cycle, the used unit for this table is Pt unit as the figure shows fossil fuels impact has the highest damage value and respiratory inorganics is in the second place. One of the options in Simapro is that you can analysis all subcategories too, by using this option many details in every category and subcategory can be obtained. In this study because of the fossil fuels high damage value we took a closer look to this subcategory which is represented in figure 4.

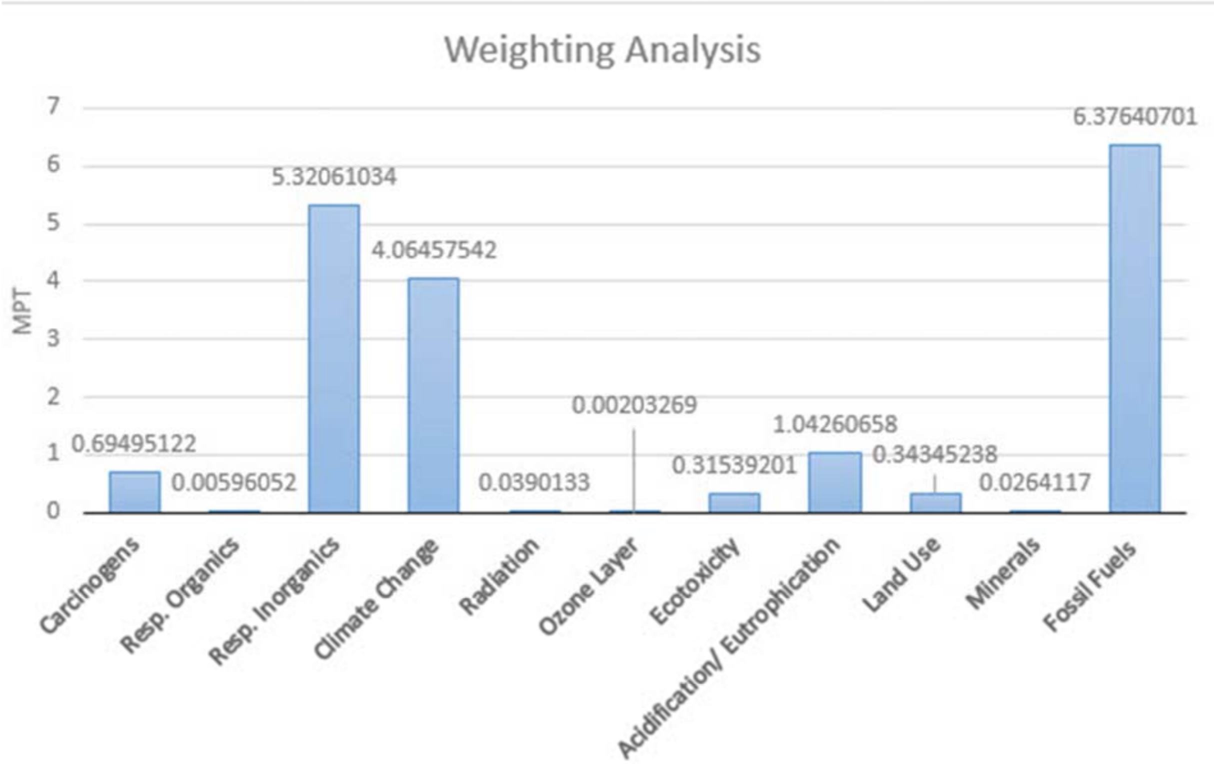
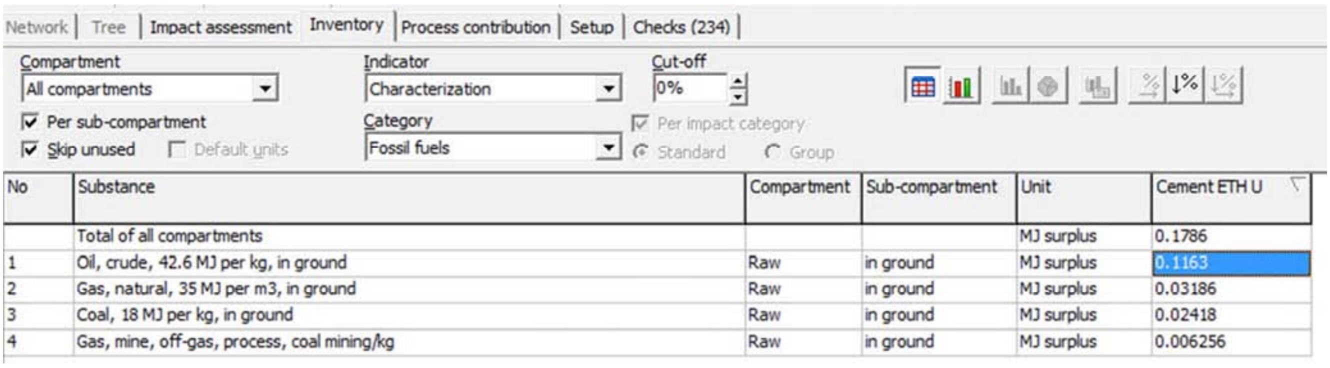


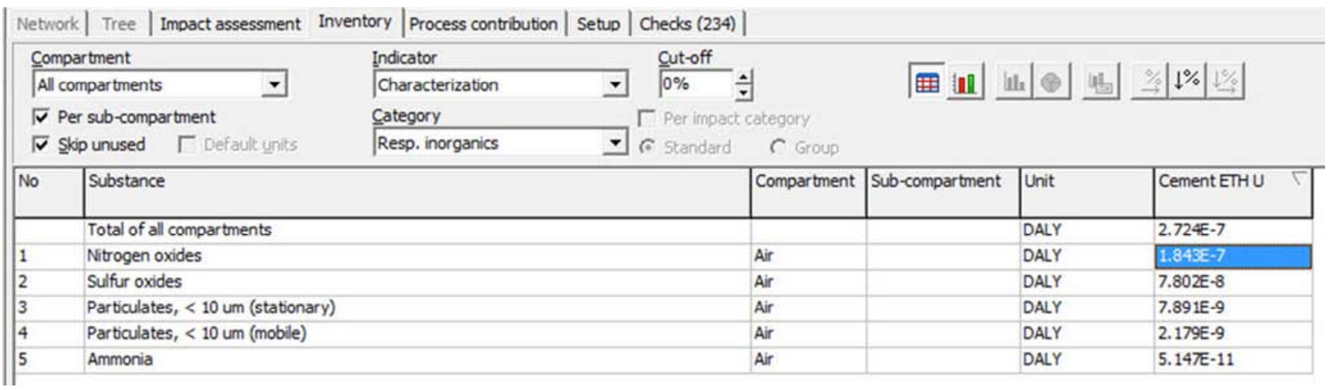
Figure 3. *Assessment of cement production per all subcategories.*



No	Substance	Compartment	Sub-compartment	Unit	Cement ETH U
	Total of all compartments			MJ surplus	0.1786
1	Oil, crude, 42.6 MJ per kg, in ground	Raw	in ground	MJ surplus	0.1163
2	Gas, natural, 35 MJ per m3, in ground	Raw	in ground	MJ surplus	0.03186
3	Coal, 18 MJ per kg, in ground	Raw	in ground	MJ surplus	0.02418
4	Gas, mine, off-gas, process, coal mining/kg	Raw	in ground	MJ surplus	0.006256

Figure 4. *Characterization of fossil fuels in cement production.*

Figure 4 shows the main substances in cement production extraction which have categorized as damage to resources. Crude oil extraction is the main reason for the damage, it needs 42.6 MJ per 1 kg crude oil extraction due to the analysis result.



No	Substance	Compartment	Sub-compartment	Unit	Cement ETH U
	Total of all compartments			DALY	2.724E-7
1	Nitrogen oxides	Air		DALY	1.843E-7
2	Sulfur oxides	Air		DALY	7.802E-8
3	Particulates, < 10 um (stationary)	Air		DALY	7.891E-9
4	Particulates, < 10 um (mobile)	Air		DALY	2.179E-9
5	Ammonia	Air		DALY	5.147E-11

Figure 5. *Characterization of resp. inorganic in cement production.*

Figure 5 shows released materials during Portland cement LCA, it also shows where these materials go after releasing with DALY unit., as the figure 5 shows Nitrogen oxides are the most released substances that has resp. inorganics effects. For climate change the same analyses is shown in table 2.

Table 1. *Portland cement production effects on climate change.*

damage assessment of climate change impact category				
No	**Substance**	**Compartment**	**Unit**	**Cement ETH U**
	Total of all compartments			2.081E-7
1	Carbon dioxide	Air	DALY	2.023E-07
2	Methane	Air	DALY	5.225E-09
3	Carbon monoxide	Air	DALY	3.783E-10
4	Dinitrogen monoxide	Air	DALY	2.3E-10
5	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-,	Air	DALY	2.336E-11
6	Methane, tetrafluoro-, FC-14	Air	DALY	7.917E-12
7	Ethane, hexafluoro-, HFC-116	Air	DALY	1.257E-12
8	Propane	Air	DALY	1.129E-12
9	Butane	Air	DALY	1.033E-12

Table 1 shows substances which are released during Portland cement LCA, these substances have effects on climate change and as it shows carbon dioxide is the most effective substance which has the highest effect.

For ecosystem quality impact category with special units table 2 prepared and units have been explained already.

Table 2. *Damage assessment of Eco toxicity impact category.*

Damage assessment of Eco toxicity impact category				
No	**Substance**	**Compartment**	**Unit**	**Cement ETH U**
	Total of all compartments			0.004043
	Remaining substances			2.451E-5
1	Nickel	Air	PDF*m2yr	0.001739
2	Zinc	Air	PDF*m2yr	0.0006931
3	Chromium	Air	PDF*m2yr	0.0004466
4	Lead	Air	PDF*m2yr	0.0003277
5	Copper, ion	Water	PDF*m2yr	0.000183
6	Nickel, ion	Water	PDF*m2yr	0.0001794
7	Chromium, ion	Water	PDF*m2yr	0.0001714
8	Copper	Air	PDF*m2yr	0.0001248
9	Cadmium	Air	PDF*m2yr	0.00007258
10	Zinc, ion	Water	PDF*m2yr	0.00004137
11	Mercury	Air	PDF*m2yr	0.000028
12	Arsenic	Air	PDF*m2yr	0.0000121

Table 2 represents damage assessment for ecotoxicity category in Portland cement production LCA, the table shows all released substances which have ecotoxicity effects on ecosystem quality with their released environment. As table represents the highest value belongs to nickel which releases to air, Since Acidification/ Eutrophication is one of the ecosystem quality subcategories, the same unit is used to describe damage assessment to this subcategory which is shown in table 3.

Table 3. *Damage assessment of Acidification/ Eutrophication impact category.*

Damage assessment of Acidification/ Eutrophication impact category			
No	**Substance**	**Unit**	**Cement ETH U**
	Total of all compartments	PDF*m2yr	0.01337
	Remaining substances	PDF*m2yr	1.735E-18
1	Nitrogen oxides	PDF*m2yr	0.01187
2	Sulfur oxides	PDF*m2yr	0.001488
3	Ammonia	PDF*m2yr	0.000009428

Table 3 shows Acidification/ Eutrophication damage substances from Portland cement production. Here are again Nitrogen oxides as the most dangerous substance in the case of damage as Acidification/ Eutrophication. For represent the most effective substances in this study just substances with high values are shown in separate tables the remaining impact categories have low effects in comparison with five impacts that analyzed above. For the remaining categories table 4 shows the analyzed damage assessment in one table.

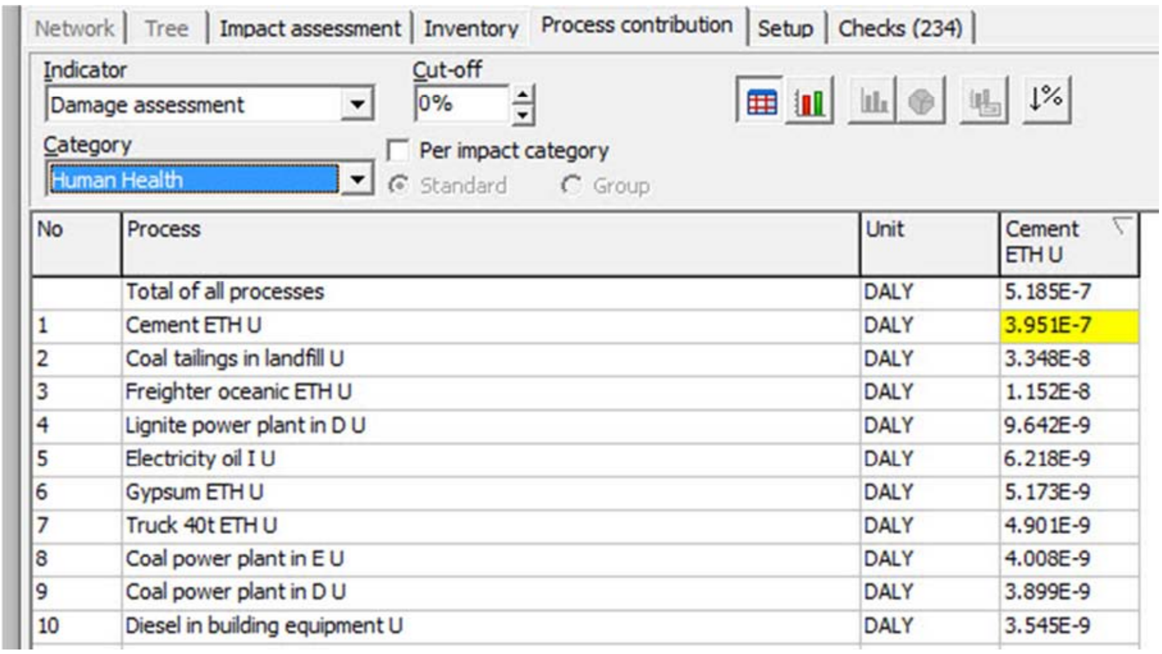
Table 4. Damage assessment for the remaining impact categories.

Damage assessment for the remaining impact categories				
No	**Substance**	**Compartment**	**Unit**	**Cement ETH U**
Carcinogens				
1	Arsenic, ion	Water	DALY	3.246E-08
2	Cadmium, ion	Water	DALY	9.613E-10
3	Cadmium	Air	DALY	9.189E-10
4	Arsenic	Air	DALY	4.613E-10
Respiratory organics				
1	NMVOC, non-methane volatile organic compounds, unspecified origin	Air	DALY	2.576E-10
2	Methane	Air	DALY	1.503E-11
3	Pentane	Air	DALY	1.647E-12
4	Butane	Air	DALY	1.175E-12
5	Xylene	Air	DALY	1.028E-12
Radiation				
1	Radon-222	Air	DALY	1.631E-9
2	Carbon-14	Air	DALY	1.626E-10
3	Cesium-137	Water	DALY	1.015E-10
4	Radon-222	Air	DALY	1.776E-11
5	Cobalt-60	Water	DALY	1.234E-11
Ozone layer				
1	Methane, bromotrifiuoro-, Halon 1301	Air	DALY	8.726E-11
2	Ethane, 1,2-dichloro-1,1,2,2-tetrafiuoro-,	Air	DALY	9.355E-12
3	Methane, trichlorofiuoro-, CFC-11	Air	DALY	4.156E-13
Minerals				
1	Iron, ion	in ground	MJ surplus	0.00001041
2	Nickel, ion	in ground	MJ surplus	3.329E-07
3	Bauxite, ion	in ground	MJ surplus	4.397E-08
4	Chromium, ion	in ground	MJ surplus	1.61E-08

Table 4 shows all the substances released during Portland cement production life cycle assessment, in mineral impact substances are in ion form which uses MJ surplus unit.

2.4. Most Critical Activities in Cement Production

In this study the most critical activities defined as the activities with same impact category which have the higher value compared to other activities in same impact category. By obtaining these activities we are able to understand which way leads us to reduce the total environmental damages. In Simapro this step called process contribution analysis. For human health figure 6 is obtained as below.



No	Process	Unit	Cement ETH U
	Total of all processes	DALY	5.185E-7
1	Cement ETH U	DALY	3.951E-7
2	Coal tailings in landfill U	DALY	3.348E-8
3	Freighter oceanic ETH U	DALY	1.152E-8
4	Lignite power plant in D U	DALY	9.642E-9
5	Electricity oil I U	DALY	6.218E-9
6	Gypsum ETH U	DALY	5.173E-9
7	Truck 40t ETH U	DALY	4.901E-9
8	Coal power plant in E U	DALY	4.008E-9
9	Coal power plant in D U	DALY	3.899E-9
10	Diesel in building equipment U	DALY	3.545E-9

Figure 6. *Damage assessment analysis of process contribution for human health during cement LCA.*

As figure 6 shows cement production process and after that coal tailings in landfill have the highest DALY damage to human health category. The same analysis for resources impacts category has been done in figure 7.

Network | Tree | Impact assessment | Inventory | Process contribution | Setup | Checks (234)

Indicator: Damage assessment — Cut-off: 0% — Category: Resources — Per impact category — Standard — Group

No	Process	Unit	Cement ETH U
	Total of all processes	MJ surplus	0.1794
1	Crude oil production onshore U	MJ surplus	0.06468
2	Crude oil production offshore U	MJ surplus	0.05161
3	Coal from underground mine UCPTE U	MJ surplus	0.01727
4	Raw natural gas NL U	MJ surplus	0.01279
5	Raw natural gas GUS U	MJ surplus	0.00811
6	Coal from open mine U	MJ surplus	0.005741
7	Raw natural gas D U	MJ surplus	0.004424
8	Raw natural gas Alg. U	MJ surplus	0.003392
9	Coal from underground mine S-Africa U	MJ surplus	0.003216
10	Raw natural gas N U	MJ surplus	0.00266
11	Coal from underground mine E-Europe U	MJ surplus	0.002355

Figure 7. *Damage assessment analysis of process contribution for resources during cement LCA.*

Figure 7 represents processes which have effects on resources depletion, in this analysis the most critical processes are the crude oil production onshore and offshore and coal mining. The last process contribution analysis have been done in figure 8 for ecosystem quality.

Network | Tree | Impact assessment | Inventory | Process contribution | Setup | Checks (234)

Indicator: Damage assessment — Cut-off: 0% — Category: Ecosystem Quality — Per impact category — Standard — Group

No	Process	Unit	Cement ETH U
	Total of all processes	PDF*m2yr	0.02181
1	Cement ETH U	PDF*m2yr	0.01285
2	Uranium natural in concentrate U	PDF*m2yr	0.002311
3	Freighter oceanic ETH U	PDF*m2yr	0.000694
4	Truck 40t ETH U	PDF*m2yr	0.0006243
5	Coal tailings in landfill U	PDF*m2yr	0.0005913
6	Infra road delivery van U	PDF*m2yr	0.0005071
7	Electricity oil I U	PDF*m2yr	0.0003562
8	Coal from open mine U	PDF*m2yr	0.000252
9	Limestone ETH U	PDF*m2yr	0.0002296
10	Lignite power plant in D U	PDF*m2yr	0.0002217
11	Gypsum stone ETH U	PDF*m2yr	0.0001838
12	Residual oil in refinery furnace Europe U	PDF*m2yr	0.0001678
13	Gypsum ETH U	PDF*m2yr	0.0001465
14	Fuel oil lowS in boiler 1MW U	PDF*m2yr	0.0001431

Figure 8. *Damage assessment analysis of process contribution for ecosystem quality during cement LCA.*

In figure 8 cement production process and uranium natural in concentrate as well as transportation processes have the highest value in damage to ecosystem quality.

3. Conclusion

From this study it's obtained that in Portland cement production from three main impact category the most affected category is human health which affected by released substances to the air, these emissions besides the human health have highly effects on resource depletion. From all emissions carbon dioxide, nitrogen oxides, sulfur oxides, methane, nickel, zinc are the most released emissions to air and arsenic, cadmium, copper, nickel, chromium and zinc ions are the most released substances to water.

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