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Life Cycle Assessment of reinforced concrete structures for building construction

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“Presto o tardi coloro che vincono

sono coloro che credono di poterlo fare”

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Abstract

Construction industry is one of the most important industries of today. The term construction refers to many activities as the building of a dam, a road, a monument, a wooden structure, a bridge, etc.

Particularly, reinforced concrete structures are the object of study in this thesis since this material a major role in the evolution of concrete contruction as it improves the behaviour of the final structure under working loads because of its high toleration of tensile strain and high relative strength.

Construction has big impacts on the environment which need to be minimised. These impacts occur from initial work on-site through the construction period, operational period and to the final demolition when a construction comes to the end of its life.

Life Cycle Assessment allows for determination of the environmental impacts at each state of a construction life cycle, beginning at the point of raw materials extraction from the earth, processing, manufacturing, fabrication, end-use and disposal. Transportation of materials and products to each process step is also included. It allows the optimization of materials and energy in order to promote sustainable development.

The following study analyse the Life Cycle using SimaPro software of several types of cements, CEM I, CEM II ALL and CEM IV A V, which are produced in different plants over Italy and compares the different scenarios in order to understand which is the one that gives lower environmental impacts. The primary data used to define each type of cement was derived from the Environmental Product Declaration (EPD) provided by Buzzi Unicem.

Two different structures are studied, one simple cylindrical bar specimen and a more complex structure with a totally different geometry. First of all, the different cements produced in each plant are compared and then it is made a comparison between plants changing the distance of the cement supplier for each type of cement. In this way it can be seen which is the cement with lowest environmental impacts and which is the plant which gives lower transport impacts.

As a following study it has been compared a particular type of cement, CEM II ALL, produced in Trino plant using the EPD data as in the previous cases and then using real primary data of the cement production provided by Buzzi.

The results obtained from the simulations have made possible to conclude which is the scenario that reduces the most the consumption of resources and the emissions to air and water under a sustainable point of view.

General overview of reinforced concrete structures

1.1 Reinforced concrete and origin

Reinforced concrete is one of the most widely used modern building materials. Concrete is obtained by mixing cement and aggregates such as sand or gravel with water but its limited tension resistance initially prevented its wide use in building construction. For this reason, steel bars are embedded in concrete to form a composite material called reinforced concrete, as shown in Figure 1:

Figure 1: Reinforced concrete structure

Reinforced concrete was designed on the principle that steel and concrete act together in resisting force. Concrete is strong in compression but weak in tension. The tensile strength is generally rated about 10 percent of the compression strength. For this reason, concrete works well for columns and posts that are compression members in a structure. But, when it is used for tension members, such as beams, girders, foundation walls, or floors, concrete must be reinforced to attain the necessary tension strength. (Integrated publishing, 2015)

Steel is the best material for reinforcing concrete because the properties of expansion for both steel and concrete are considered to be approximately the same, that is, under normal conditions, they will expand and contract at an almost equal rate.

Joseph Monier generally deserves the credit for making the first practical use of reinforced concrete in 1849 to 1867. He acquired first French patent in 1867 for iron reinforced concrete tubs, then followed by pipes, tanks in 1868, flat plates in 1869, bridges in 1873 and stairways in 1875.

In the United States, the pioneering was made by Thaddeus Hyatt, who conducted experiments on reinforced concrete beams in 1850s. In 1890, Ransome built the Leland Stanford Jr. Museum in San Francisco, a reinforced concrete building displayed in Figure 2. Since that time, development of reinforced concrete has been rapid. (Engineer's outlook, 2011)

Figure 2: First reinforced steel building by E.L. Ransome

1.2 Common cements and cements requirements

Certain chemical and physical limits are placed on cements to ensure a level of consistency between cement-producing plants. These chemical limits are defined by a variety of standards and specifications. For instance, Portland cements and blended hydraulic cements for concrete in the U.S. conform to the American Society for Testing and Materials (ASTM) C150 (Standard Specification for Portland cement).

In building construction different types of cements can be manufactured since structures have various chemical and physical requirements (See Table 1). The most common one is Portland cement and it is created by burning limestone with other materials at 1450°C. The result is then ground to produce a fine powder, which becomes one of the components of concrete. Altering the amounts of the other materials in the burnt mixture yields several different types of Portland cement, however, each type having unique properties and strength. (The Science of Concrete, 2014)

Table 1: Different types of cements

Main types	Notation of the 27 products (types of common cement)		Composition [proportion by mass 1)]										
			Main constituents										Minor additional constituents
			Clinker	Blastfurnace slag	Silica fume	Pozzolana		Fly ash		Burnt shale	Limestone*		
						natural	natural calcined	siliceous	calcareous				
			K	S	D 2)	P	Q	V	W	T	L	LL	
CEM I	Portland cement	CEM I	95-100	-	-	-	-	-	-	-	-	-	0-5
CEM II	Portland-slag cement	CEM II/A-S	80-94	6-20	-	-	-	-	-	-	-	-	0-5
		CEM II/B-S	65-79	21-35	-	-	-	-	-	-	-	-	0-5
	Portland-silica fume cement	CEM II/A-D	90-94	-	6-10	-	-	-	-	-	-	-	0-5
	Portland-pozzolana cement	CEM II/A-P	80-94	-	-	6-20	-	-	-	-	-	-	0-5
		CEM II/B-P	65-79	-	-	21-35	-	-	-	-	-	-	0-5
		CEM II/A-Q	80-94	-	-	-	6-20	-	-	-	-	-	0-5
		CEM II/B-Q	65-79	-	-	-	21-35	-	-	-	-	-	0-5
	Portland-fly ash cement	CEM II/A-V	80-94	-	-	-	-	6-20	-	-	-	-	0-5
		CEM II/B-V	65-79	-	-	-	-	21-35	-	-	-	-	0-5
		CEM II/A-W	80-94	-	-	-	-	-	6-20	-	-	-	0-5
		CEM II/B-W	65-79	-	-	-	-	-	21-35	-	-	-	0-5
	Portland-burnt shale cement	CEM II/A-T	80-94	-	-	-	-	-	-	6-20	-	-	0-5
		CEM II/B-T	65-79	-	-	-	-	-	-	21-35	-	-	0-5
	Portland-limestone cement	CEM II/A-L	80-94	-	-	-	-	-	-	-	6-20	-	0-5
		CEM II/B-L	65-79	-	-	-	-	-	-	-	21-35	-	0-5
		CEM II/A-LL	80-94	-	-	-	-	-	-	-	-	6-20	0-5
		CEM II/B-LL	65-79	-	-	-	-	-	-	-	-	21-35	0-5
	Portland-composite cement 3)	CEM II/A-M	80-94	<------ 6-20 ------									0-5
		CEM II/B-M	65-79	<------ 21-35 ------									0-5
CEM III	Blastfurnace cement	CEM III/A	35-64	36-65	-	-	-	-	-	-	-	-	0-5
		CEM III/B	20-34	66-80	-	-	-	-	-	-	-	-	0-5
		CEM III/C	5-19	81-95	-	-	-	-	-	-	-	-	0-5
CEM IV	Pozzolanic cement 3)	CEM IV/A	65-89	-	<------ 11-35 ------>					-	-	-	0-5
		CEM IV/B	45-64	-	<------ 36-55 ------>					-	-	-	0-5
CEM V	Composite cement 3)	CEM V/A	40-64	18-30	-	<------ 18-30 ------>			-	-	-	-	0-5
		CEM V/B	20-38	31-50	-	<------ 31-50 ------>			-	-	-	-	0-5

1) The values in the table refer to the sum of the main and minor additional constituents. 2) The proportion of silica fume is limited to 10%.

3) In Portland-composite cements CEM II/A-M and CEM II/B-M, in Pozzolanic cements CEM IV/A and CEM IV/B and in Composite cements CEM V/A and CEM V/B the main constituents besides clinker shall be declared by designation of the cement.

* L : total organic carbon (TOC) shall not exceed 0.5% by mass; LL: TOC shall not exceed 0.20% by mass.

Regarding chemical and physical tests requirements, chemical tests verify the content and composition of cement while physical testing demonstrates physical criteria.
Some examples of chemical tests include oxide analyses (SiO_2, CaO, Al_2O_3, Fe_2O_3, etc.) to allow the cement phase composition to be calculated and some physical requirements can be air content, fineness, expansion, strength, heat of hydration, and setting time.

1.3 Aggregates types

Aggregates are inert granular materials such as sand, gravel, or crushed stone. For a good concrete mix, aggregates need to be clean, hard, strong particles free of absorbed chemicals or coatings of clay and of other fine materials that could cause the deterioration of concrete. (Portland cement association, 2016)

Aggregates are divided into two categories, according to (CivilBlog, 2014):

1.3.1 Fine aggregates:

It is the aggregate most of which passes 4.75 mm IS sieve and contains only so much coarser as it is permitted by specification. According to source fine aggregate may be described as:

- Natural Sand: it is the aggregate resulting from the natural disintegration of rock and which has been deposited by streams or glacial agencies
- Crushed Stone Sand: it is the fine aggregate produced by crushing hard stone.
- Crushed Gravel Sand: it is the fine aggregate produced by crushing natural gravel

1.3.2 Coarse aggregates:

It is the aggregate most of which passes 4.75 mm IS sieve and contains only so much coarser as it is permitted by specification. According to source coarse aggregate may be described as:

- Uncrushed Gravel or Stone: it results from natural disintegration of rock
- Crushed Gravel or Stone: it results from crushing of gravel or hard stone.
- Partially Crushed Gravel or Stone: it is a product of the blending of the above two aggregate.

1.4 Reinforced concrete: Mix Design and Installation

Once the amount of cement, aggregates and water have been chosen then all are mixed in a concrete mixer, which homogenously combines all those components to form concrete. A revolving drum is used to mix them and it is powered by electric motors using standard mains current. The concrete mixer was invented by Columbus industrialist Gebhardt Jaeger. (PhD Talk, 2011)

Figure 3: Concrete mixer (1) and mix falling down by gravity into the formwork (2)

After that, the mix falls down by means of gravity on a vibrator concrete machine with the formwork placed on its surface (See Figure 3). The reinforcing steel is inside the formwork as it can be seen in the following figure, so the concrete fills completely the mold and dries.

The reason of using a vibrator machine is that it consolidates freshly poured concrete so that trapped air and excess water are released and the concrete settles firmly in place in the formwork (See Figure 4). Otherwise, defects can be caused, concrete strength can be compromised and surface blemishes such as bug holes can be produced.

Figure 4: Reinforcing bars placed at the formwork (1) and concrete vibrator machine (2)

Finally, it starts the curing period, it is the hydration process that occurs after the concrete has been placed and allows the concrete to achieve optimal strength and hardness.

Life Cycle Assessment

2.1 Life Cycle Assessment: Origin

The first well-known environmental study was conducted in 1969 by Coca-Cola. This study showed that all containers had an environmental impact, and this impact is stronger or lower depending on the materials. Therefore, Coca Cola collaborated to recycle aluminum cans and so their energy consumption was reduced by 90%.

In 1979, the Society of Environmental Toxicology and Chemistry (SETAC) was founded to serve as a non-profit professional society to solve environmental problems.

In the late 1980s, life-cycle assessment emerged as a tool to better understand the risks, opportunities and trade-offs of product systems as well as the nature of environmental impacts. At the first SETAC-sponsored international workshop in 1990, the term “life cycle assessment” (LCA) was defined.

Beginning in 1993, the International Organization for Standardization (ISO) regarded the need to standardize LCA and by 1997 the ISO14040 standard for Life cycle assessment – Principles and framework was complete.

In 2002, the United Nations Environment Programme (UNEP), SETAC and partners from government, academia, civil society, business and industry joined forces to promote life cycle approaches worldwide. (Gabi-software, 2016)

2.2 Concept of Life Cycle Assessment

The Life Cycle Assessment is a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle (*ISO 14040: 2006).*

2.3 Stages of a Life Cycle Analysis

Life cycle analysis related to a product examines the environmental impacts by considering the major stages of a product's life.

Figure 5: Life cycle stages

The main stages (Illinois Sustainable Technology Center, 2013), as shown in Figure 5, include:

- Resource extraction and raw material acquisition: this includes material harvesting and transportation to manufacturing sites.
- Processing: this involves material processing and transportation to production sites.
- Manufacturing: this includes product manufacture and assembly, packaging and transportation to final distribution.
- Product life: this includes energy and emissions during normal product life and maintenance.
- End of life: this includes recycling, re-use, energy recovery and disposal.
- Waste management: this includes liquid waste, gas emissions, etc.

When defining a life cycle analysis, it is important to clearly define the inputs and outputs of a process or product (See Figure 6Figure 6: Life cycle inputs and outputs of a general process). Inputs include energy and raw materials while outputs include various types of products and wastes.

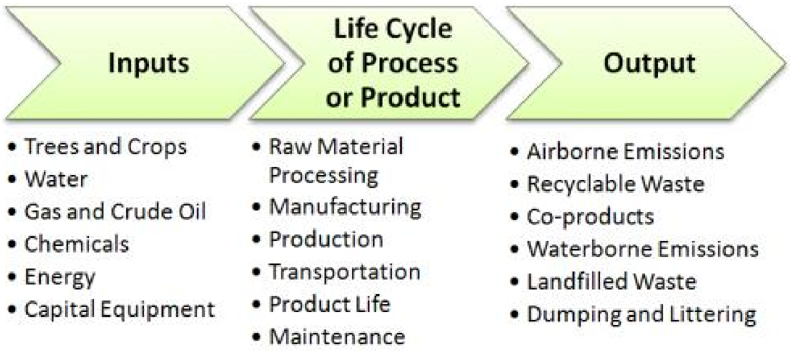

Figure 6: Life cycle inputs and outputs of a general process

2.4 Steps of a Life Cycle Assessment study

Attending to *ISO 14040:2006* the LCA technique can be narrowed down to four main steps, displayed in Figure 7:

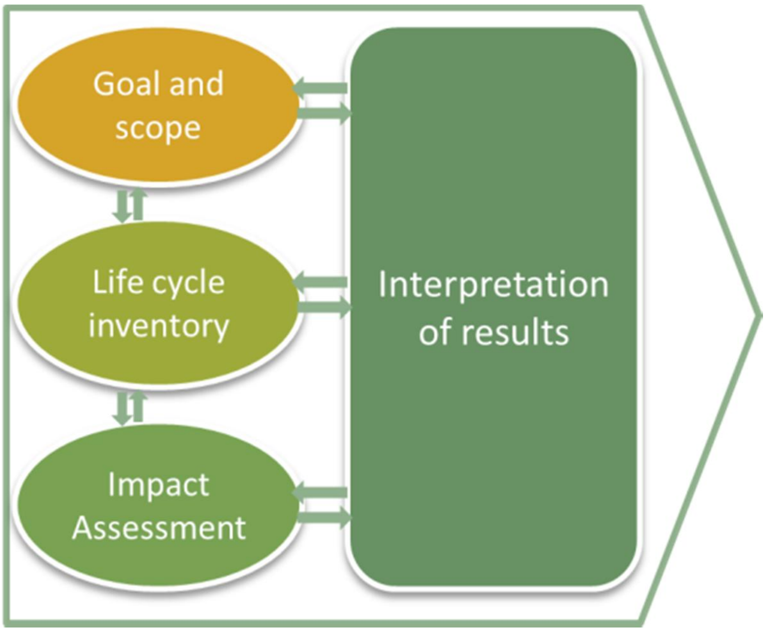

Figure 7: Life Cycle Assessment steps according to ISO standards

2.4.1 Goal and scope definition: it is determined along information needs, data specify, collection methods and data presentation.

The goal must be defined attending to the origin of the study, the expected application, the audience (end consumer, stakeholders, manufacturers, processors, recyclers…) and the product or process comparison options.
However, the scope must be defined according to:

- Product system: collection of processes materially and energetically interconnected which can be used as a model to study the life cycle of a product.
- System boundaries: processes of the product system which are included in the study.
- System functions
- Functional unit: the functional unit, which defines what precisely is being studied and quantifies the service delivered by the product system, providing a reference to which the inputs and outputs can be related. Further, the functional unit is an important basis that enables alternative goods, or services, to be compared and analyzed.

- Allocation methods: when the product system develops more than one function or produces more than one product it is necessary to distribute the input and/or output flows of a process to the product system under study. The solutions can be:

  - System boundaries expansion: In order to include the obtainment of the other products and functions.
  - Economical or mass assignment, or a combination of both of them.

- Impact categories: it is also important to consider how the results of the life cycle inventory affect the world around us.
- Assumptions and limitations
- Data requirements
- Data quality requirements: reliability of the results from LCA studies strongly depends on the extent to which data quality requirements are met. Some parameters are:

  - Time-related coverage.
  - Geographical coverage.
  - Technology coverage.
  - Precision, completeness and representativeness of the data.
  - Consistency and reproducibility of the methods used throughout the data collection.
  - Uncertainty of the information and data gaps.

2.4.2 Life cycle Inventory (LCI)

It is a process which quantifies all inputs and outputs of a process or product. It is also a way to develop a comparison of the environmental impacts and potential improvements of the process or product. (Global development research center, 2015)

The data collection forms must be properly designed for optimal collection. Subsequently data is validated and related to the functional unit in order to allow the aggregation of results.

There are two types of data in a LCI:

- Activity data: material and energetic resources, transport, waste, etc associated to the product. They must be referred to the functional unit.
- Emission factors: they relate the quantities expressed in the activity data with the elementary flows (for example CO_2, SO_2, CH_4…)

Both activity data and emission factors can be:

- Primary data: obtained from direct measurements
- Secondary data: referred to measurements outside the process which are not specific of the product, they represent an average between processes, materials or technologies.

The life Cycle Inventory procedure can be summarized in Figure 8:

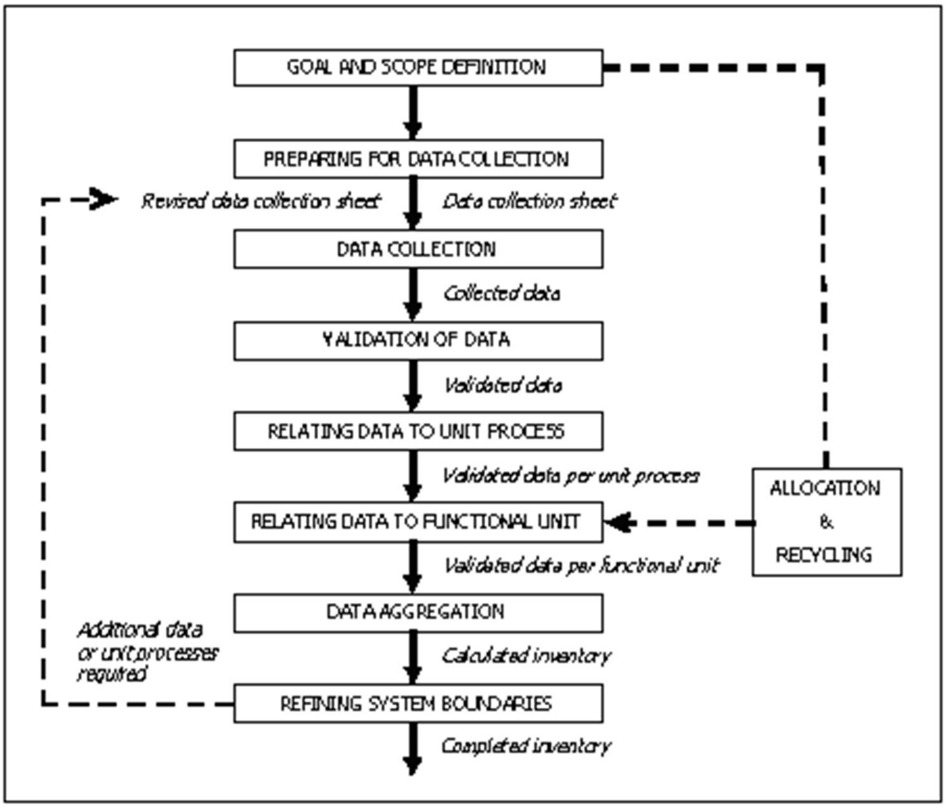

Figure 8: Life Cycle Inventory procedure

A materials database is a database used to store experimental, standards or design data for materials in such a way that they can be retrieved efficiently by humans or computer programs. The one that will be used in this thesis work is Ecoinvent, its logo can be seen in Figure 9.

Figure 9: Ecoinvent Logo

2.4.3 Life cycle impact assessment (LCIA)

It is a way to interpret how the processes and products in the LCA impact human health, the environment and availability of natural resources. Therefore, the LCIA considers the LCI data but gives it a more meaningful basis for comparison.

According to ISO 14042 there are several steps when performing a LCIA:

1. Impact category selection: stage in which both impact categories and methodology to be followed are selected. These impact categories include climate change, ozone depletion, eutrophication, acidification, human toxicity (cancer and non-cancer related), respiratory inorganics, ionizing radiation, ecotoxicity, photochemical ozone formation, land use, and resource depletion. The emissions and resources derived from LCI are assigned to each of these impact categories. They are represented by indicators which can be midpoint indicators (substance level, only environmental dimension) or endpoint indicators (also damage level, damage caused).

2. Classification: stage in which inventory data is assigned to each impact category.

3. Characterization: stage in which inventory data is quantified and added, using characterization factors (See Table 2), to the different impact category.

Table 2: : Impact cathegories and their related characterization factor unit

The following form may be used to report baseline indicator results and any other relevant information:

impact category	amount	unit
depletion of abiotic resources	.....	kg (antimony eq.)
effects of land use		
land competition	.....	m^2.yr
climate change	.....	kg (CO_2 eq.)
stratospheric ozone depletion	.....	kg (CFC–11 eq.)
human toxicity	.....	kg (1,4-DCB eq.)
ecotoxicity		
fresh water aquatic ecotoxicity	.....	kg (1,4-DCB eq.)
marine ecotoxicity	.....	kg (1,4-DCB eq.)
terrestrial ecotoxicity	.....	kg (1,4-DCB eq.)
photo-oxidant formation	.....	kg (C_2H_4 eq.)
acidification	.....	kg (SO_2 eq.)
eutrophication	.....	kg (PO_4^{3-} eq.)
interventions for which characterisation factors are lacking		
...	...	...
...	...	...
...	...	...
economic flows not followed to system boundary		
...	....	...
...	...	...
...	...	...
other remarks (including qualitative assessment, 'red flags', etc.)		

2.4.4 Data interpretation

The last step of LCA is the interpretation facilitated by normalization and occasionally weighting. Normalization is the stage in which the relative contributions of the different impacts are valuated according to a reference value.

On the other hand weighting is the stage in which the data of the different impact categories is weighted and added in order to obtain a unique result or environmental index. (Pre-sustainability, 2016)

The following Figure 10 summaries both the stages of a LCA and all the steps to be followed to perform the Life Cycle Analysis:

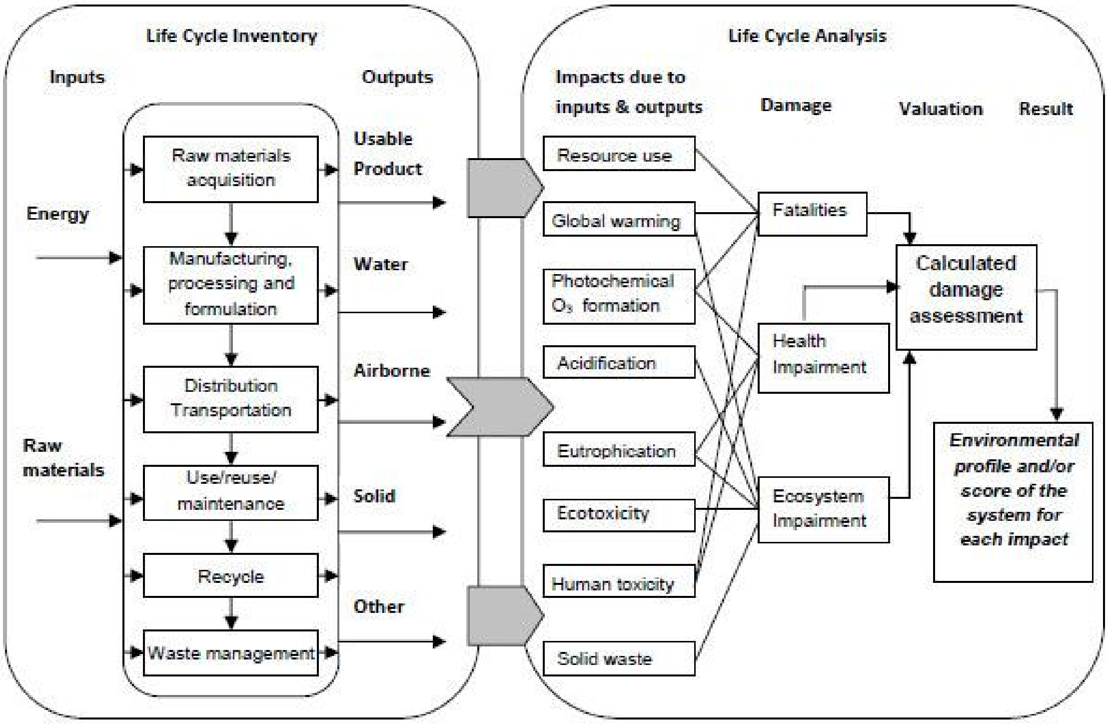

Figure 10: An overview of LCA

2.5 The impact evaluation methods

Impact evaluation methods are quantitative methods where the impact potential of the different substances is quantified by assigning them their characterization factors for the different impact categories. (Gabi-software, 2016)

Some of the methods used by software programs are:

- CML 2001
- Cumulative energy demand
- Eco-indicator 99
- Ecological footprint
- Ecological scarcity 1997 and 2006
- Ecosystem damage potential – EDP
- EDIP'97 and 2003 - Environmental Design of Industrial Products
- EPS 2000 - environmental priority strategies in product development
- IMPACT 2002+ • IPCC 2001 (climate change) and IPCC 2007 (climate change)
- ReCiPe (Midpoint and Endpoint approach)
- TRACI
- USEtox

2.6 SimaPro Software

There are different softwares to perform a LCA such us Eco-it, Gabi, SimaPro, Team, Wisard, Umberto. The one that will be used during this thesis is SimaPro.

The LCA software SimaPro is developed by PRé Consultants in the Netherlands, with an international network of LCA specialists. It is the leading LCA software product in the world. ESU-services Ltd. has started using SimaPro with the first release of Ecoinvent data in 2003. (Esu-Services, 2016)

SimaPro (See logo in Figure 11) satisfies all the needs to perform a LCA as it comes with extensive databases of LCI data including the ecoinvent data and also all the common methods of LCIA. This allows for efficient and transparent LCA, with reliable data and methods.

Figure 11: SimaPro Logo

Life Cycle Assessment of reinforced concrete for a building construction

3.1 Life Cycle Assessment of reinforced concrete structures

A life cycle assessment method and model should take into account all important environmental impacts within the whole life of a reinforced concrete product, from raw materials acquisition up to demolition and reuse of the materials or waste disposal. (P.Hajek et al, 2012)

The typical life cycle of reinforced concrete structure usually includes the following life stages:

1. Raw material acquisition (acquisition of the binder, water, aggregates, steel, etc).
2. Production and transport of basic structural materials.
3. Design and optimization of the concrete mix, the concrete element and the concrete structure.
4. Production of the concrete mix, including transportation to the construction site.
5. Production of structural components and technological equipment, including transportation to the construction site (precast elements, formwork)
6. Installation of the reinforced concrete element.
7. Construction of the concrete structure (building, bridge, roads…)
8. Maintenance of the concrete structure
9. Repairs of failures
10. Renovation and rebuilding
11. Demounting and/or demolition
12. Reuse of upgraded concrete elements
13. Recycling of concrete elements and concrete wastes
14. Concrete waste disposal.

The quality level of performance of a reinforced concrete structure in a specific life cycle stage (See Figure 12) is determined by the initial quality of the structure achieved during the construction process, so it varies depending on the type of materials used and the amounts. A higher initial investment in higher quality can result in lower operational costs and lower total environmental or financial costs at the end of the life cycle of the reinforced concrete structure.

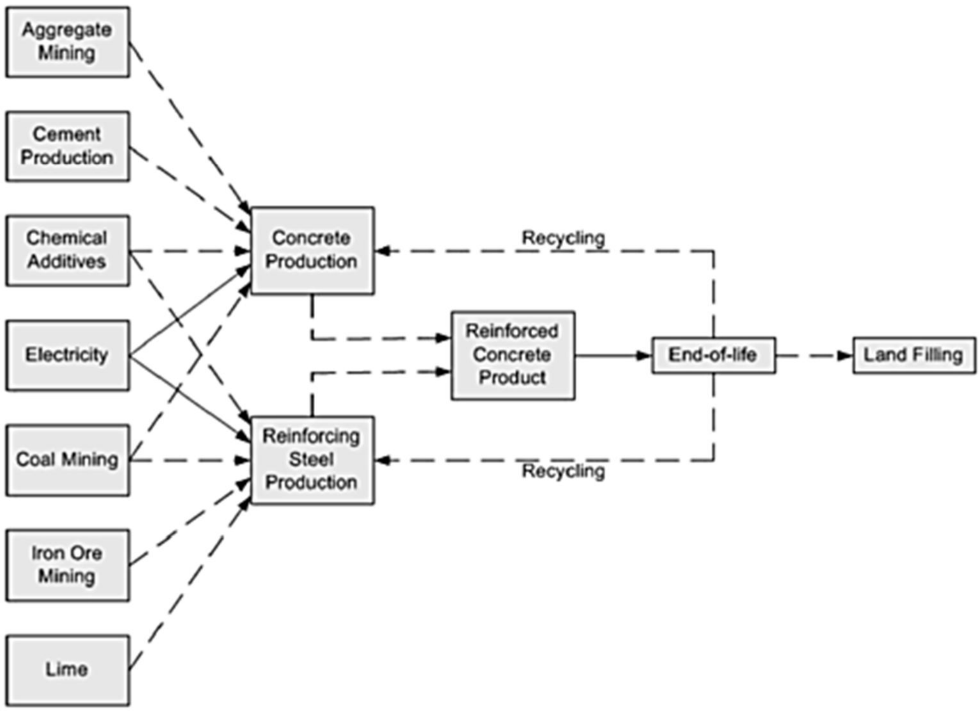

Figure 12: Life Cycle phases of a reinforced concrete structure

3.2 Literature review of reinforced concrete structures

Reinforced concrete is not a new concept. Several studies have been made about this topic and several articles have been written. What follows is a brief examination of some life cycle assessments of reinforced concrete structures. These papers have been chosen in order to represent different hypothesis, as different types and amounts of the materials used, procedures to be followed and goals to study the environmental impacts of reinforced concrete in different structures. According to the results, building construction can be improved in future studies. These papers will be summarized in the following Table 3:

Table 3: Literature review concerning LCA of reinforced concrete structures

Title	Authors	Country and date	Procedure
Lowering the global warming impact of bridge rehabilitations by using Ultra High Performance Fibre Reinforced Concretes	G. Habert et al	Ljubljana, Slovenia, 2012	Lowering the global warming impact
A comparative cradle-to-gate life cycle assessment of three concrete mix designs	Michael W. Tait et al	United States, 2016	Comparison of several mix designs
Environmental evaluation of concrete made from recycled concrete aggregate implementing life cycle assessment	Nicolas Serres et al	Strasbourg, France, 2015	Comparison of recycled and traditional mix designs also changing the length of the specimens
Environmental evaluation of green concretes versus conventional concrete by means of LCA	Janez Turk et al	Ljubljana, Slovenia, 2015	Comparison between green concrete mixes and recycled concrete mixes with different aggregates and admixtures
Comparing the midpoint and endpoint approaches based on ReCiPe—a study of commercial buildings in Hong Kong	Ya Hong Dong et al	Hong Kong, China, 2013	Comparing two different approaches based on ReciPe method
A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies	Deborah N. et al	Michigan, UK, 2009	Comparing different types of cements using LCA

3.2.1 Lowering the global warming impact of bridge rehabilitations by using Ultra High Performance Fibre Reinforced Concretes (G. Habert et al, 2012)

The objective of the present study is to evaluate the global warming impact of bridge rehabilitations with different types of UHPFRC (Ultra-High Performance Fibre Reinforced Concretes) and to compare them to more standard solutions, both on the basis of the bridge rehabilitation performed in Slovenia. Life Cycle Assessment is the methodology used.

UHPFRCs are characteri zed by a very low water/binder ratio, high powders content and an optimized fibrous reinforcement, with an extremely low permeability and outstanding mechanical properties.

Three systems are compared in this study:

- The first one follows the solution presented on Figure 13(a) using the ECO-UHPFRC (Eco-friendly UHPFRC)
- The second one follows the solution presented on Figure 13(b), but just using UHPFRC.
- The third one is a traditional rehabilitation system using conventional concrete and a waterproofing membrane, Figure 13(b).

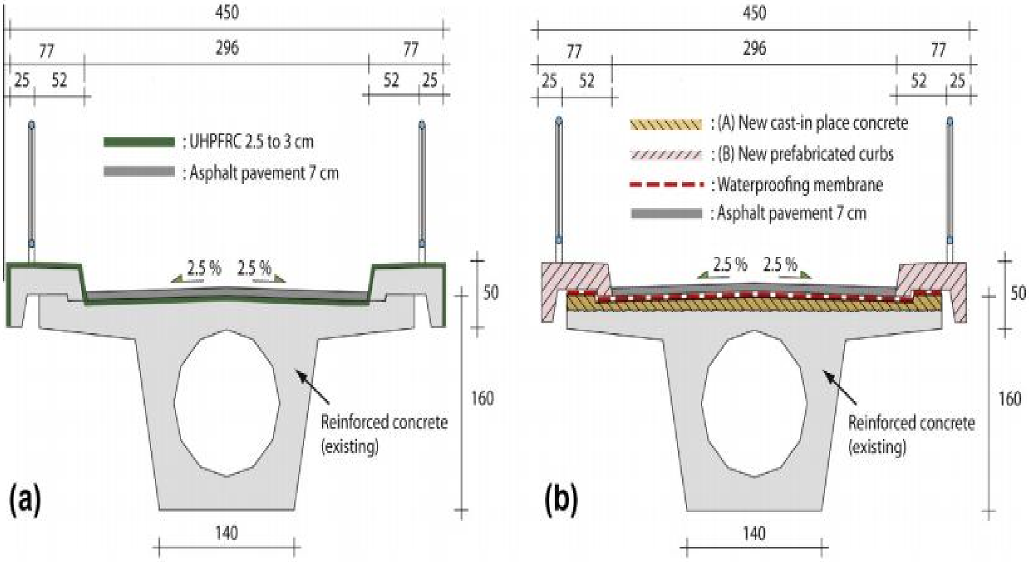

Figure 13: Rehabilitation systems (a) Application of UHPFRC (b) Rehabilitation system using conventional concrete and a waterproofing membrane

The boundaries of the studied system includes phases from the acquisition of raw materials to repair and maintenance as it can be seen in the following Figure 14:

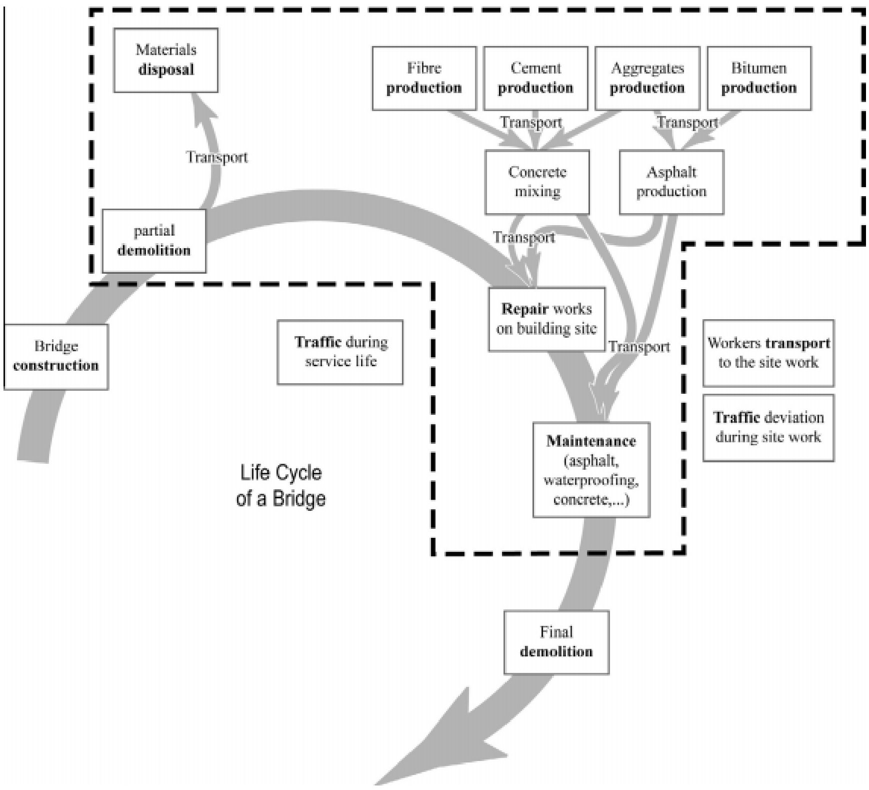

Figure 14: System boundaries of the studied system

The life cycle assessment analysis shows that rehabilitations with UHPFRC and even more with ECO-UHPFRC have lower impacts than traditional methods over the life-cycle.

3.2.2 A comparative cradle-to-gate life cycle assessment of three concrete mix designs (Michael W.Tait et al, 2016)

In this case the overall environmental impact is evaluated by means of three different concrete mixes using SimpaPro 8. The type and amount of materials are shown in the following Table 4:

Table 4: Material content of each concrete mix design

Material	Mix 1: CEM I (kg/m^3)	Mix 2: CEM II/B-V (kg/m^3)	Mix 3: CEM III/B (kg/m^3)
PC	380	247	114
GGBS	0	0	266
FA	0	133	0
10/20-*mm limestone Aggregate*	615	606	610
4/10-*mm limestone Aggregate*	413	407	410
0–4-*mm Fine aggregate*	806	794	800
Plasticiser	2	2	2
Water	190	190	190
TOTAL:	*2406*	*2379*	*2392*

The boundaries taken include raw material acquisition, transportation, mix design and installation as it is shown in the following Figure 15*:*

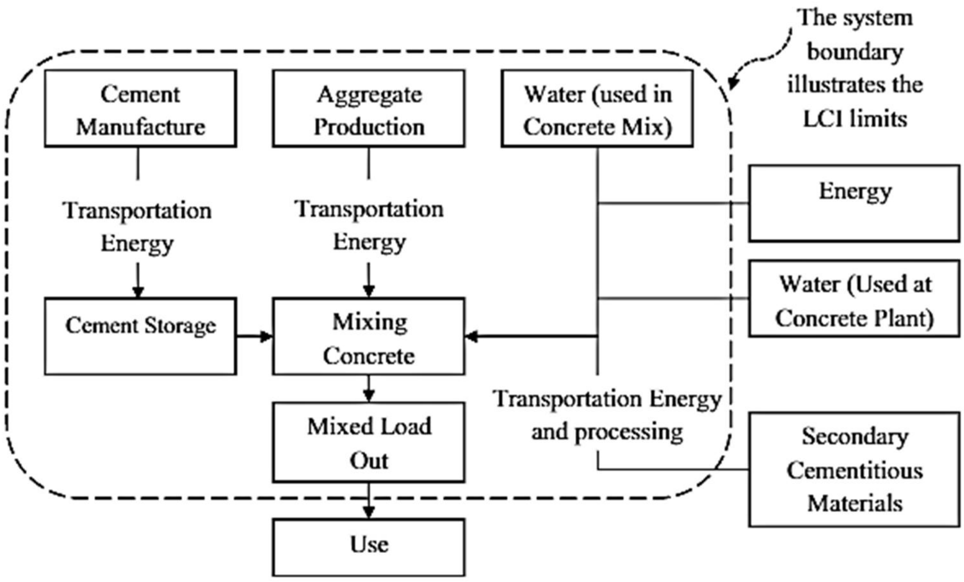

Figure 15: Concrete production system boundary

From the results obtained it can be seen that fly ash does still considerably improve sustainability when compared to PC, but this work proved that inclusion of GGBS (Ground granulated blast-furnace slag) environmentally optimizes the mix design by reducing CO_2 emissions (See Figure 16).

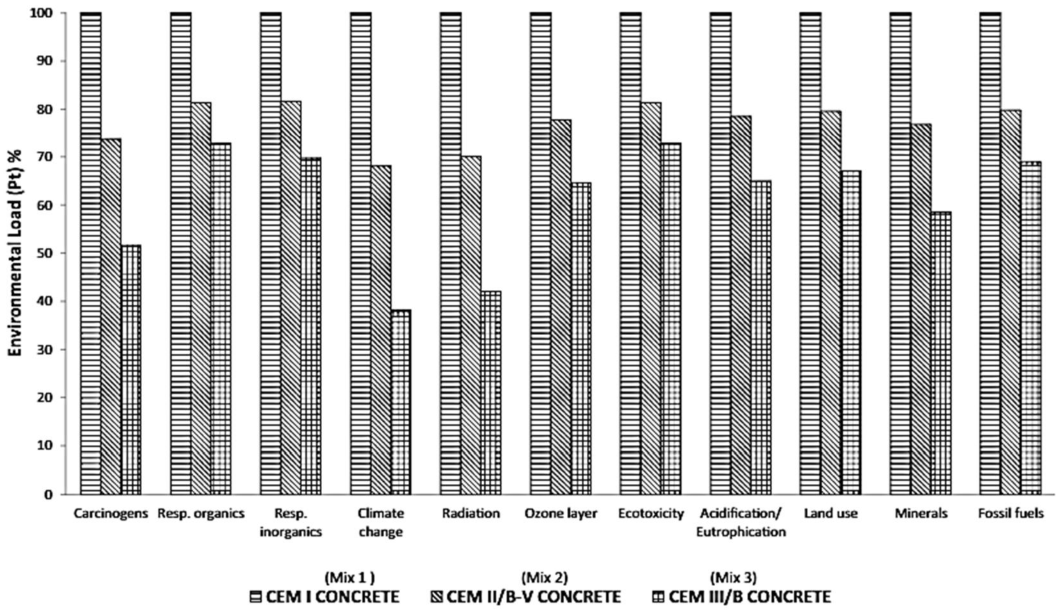

Figure 16: Environmental impacts of the three mixes

3.2.3 Environmental evaluation of concrete made from recycled concrete aggregate implementing life cycle assessment (Nicolas Serres et al, 2015)

The paper is based on three different mix designs, one traditional (natural sand and natural gravel), another one mixed (with natural sand and recycled gravel) and the last one recycled (with both recycled sand and recycled gravel) on both 20 mm concrete samples and 8 mm concrete samples.

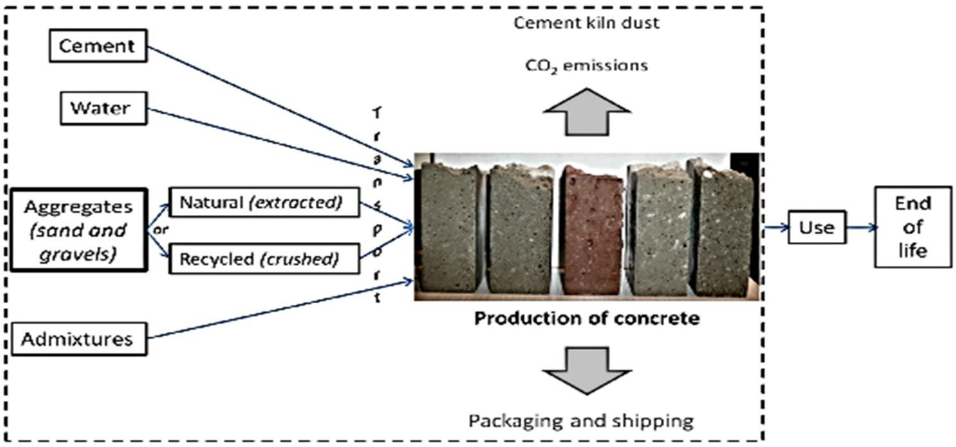

Figure 17: Life cycle of the concrete samples

In this case the boundaries of the system are extended from the acquisition of materials to the manufacturing (including packaging and shipping) of the concrete samples as it can be seen in Figure 17.

It is finally concluded that both in the 20 mm and 8 mm concrete samples the recycle concrete sample is the one that presents the best environmental behavior so the development of concrete formulated with recycled aggregates can be interesting to limit the storage of construction wastes, in order to reduce the waste storage areas and the environmental footprint (See Figure 18 and Figure 19).

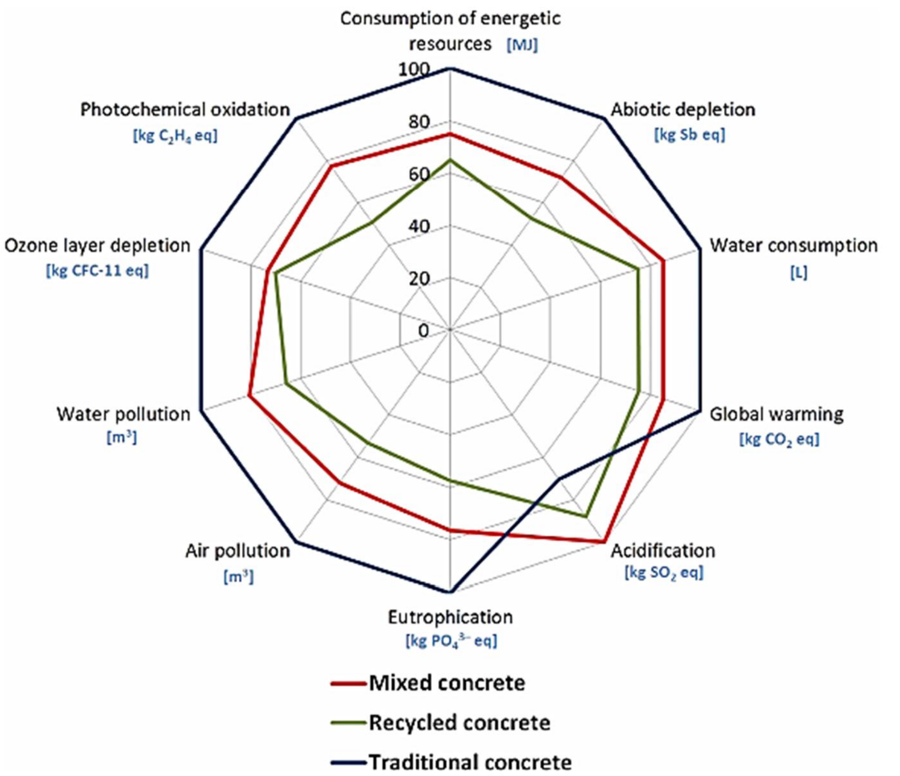

Figure 18: Environmental assessment of the 20-mm concrete samples

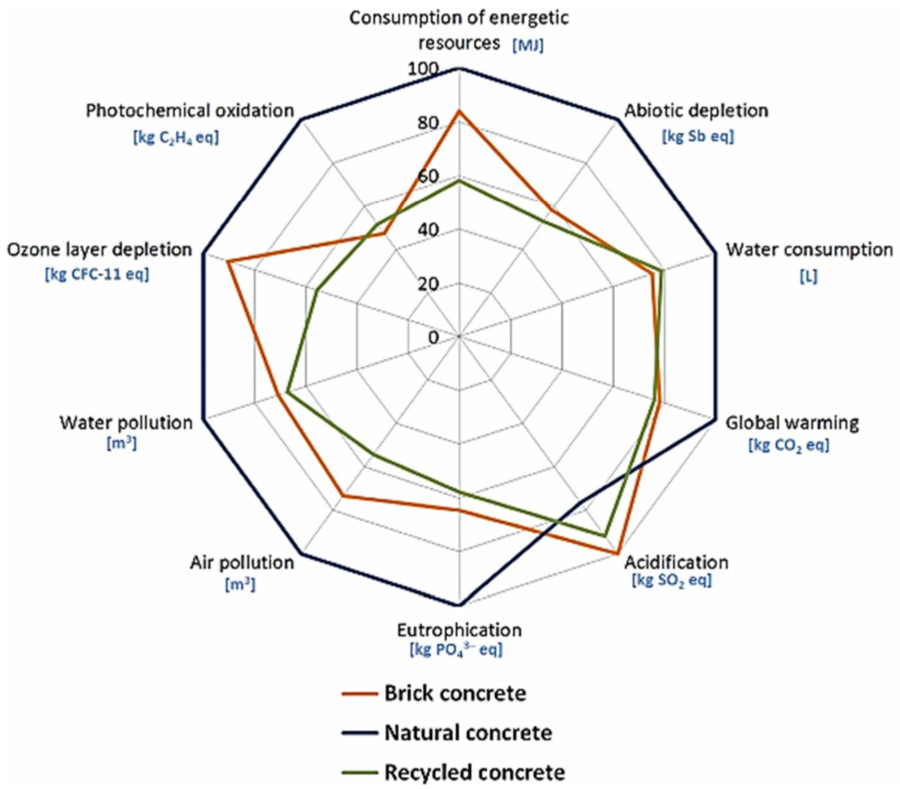

Figure 19: Environmental assessment of the 8-mm concrete samples

3.2.4 Environmental evaluation of green concretes versus conventional concretes by means of LCA (Janez Turk et al, 2015)

A number of green concrete mixes having similar basic properties were evaluated from the environmental point of view by means of the Life Cycle Assessment method, and compared with a corresponding conventional concrete mix. The investigated green concrete mixes were prepared from three different types of industrial by-products:

- Foundry sand, it is used as an aggregate.
- Steel slag, it is also used as an aggregate.
- Fly ash, it is used to replace Portland cement.

Some green concrete mixes were also prepared from a recycled aggregate, which was obtained from reinforced concrete waste.

All mix proportions are summarized in the following Table 5 and Table 6:

Table 5: Mix proportions for different green concrete mixes

The mix proportions for different green concrete mixes (based on the use of alternative materials) compared to the conventional concrete mix.

Raw material	Conventional concrete	Green concrete based on fly ash	Green concrete based on foundry sand	Green concrete based on steel slag
Aggregate (kg/m^3)	1926	1867	1660	1771
Fly ash (kg/m^3)	/	80	/	/
Steel slag (EAF S) (kg/m^3)	/	/	/	106
Foundry sand (kg/m^3)	/	/	293	/
Cement (kg/m^3)	320	240	280	320
Water (kg/m^3)	175	174	164	190
Plasticizer (kg/m^3)	2	2	2	2
			Total mass (kg/m^3)	
	2423	2363	2399	2389

Table 6: Mix proportions for the recycled concrete mixes

Raw material	Conventional oncrete	Recycled concrete based on recycled aggregate	Green concrete based on recycled aggregate and fly ash	Green concrete based on recycled aggregate and foundry sand	Green concrete based on recycled aggregate and steel slag
Aggregate (kg/m^3)	1926	1315	1269	1088	1213
Recycled aggregate (kg/m^3)	/	564	544	577	520
Fly ash (kg/m^3)	/	/	80	/	/
Steel slag (EAF S) (kg/m^3)	/	/	/	/	106
Foundry sand (kg/m^3)	/	/	/	289	/
Cement (kg/m^3)	320	320	240	280	320
Water (kg/m^3)	175	183	199	180	199
Plasticizer (kg/m^3)	2	2	2	2	2
				Total mass (kg/m^3)	
	2421	2384	2334	2386	2360

In this study system boundaries do not include construction, use and end of life phases.

Results shown in this case significant differences between impact cathegories depending on the combination of concrete mixes and mix proportions concluding that green concretes in combination with steel slag shows much more improvement than the others with respect to Eutrophication cathegory. However, recycled concrete mixes present much more benefits and improvements.

3.2.5 Comparing the midpoint and endpoint approaches based on ReCiPe—a study of commercial buildings in Hong Kong (Ya Hong Dong et al, 2015)

This paper examines 23 materials accounting for over 99 % of the environmental impacts of all the materials consumed in commercial buildings in Hong Kong. The midpoint and endpoint results are compared at the normalization level. A commercial building in Hong Kong is further studied to provide insights as a real case study.

Conclusions suggest that midpoint approach is able to provide analysis for a set of impact categories despite the results are difficult to interpret while endpoint approach includes the damage assessment and introduces more uncertainties to the results. The midpoint approach is in general preferred since it can provide reliable assessment, while the endpoint approach gives additional information of damage with a higher degree of interpretation.

3.2.6 A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies (Deborah N. Huntzinger et al, 2009)

This paper uses LCA to evaluate the environmental impact of four cement manufacturing processes:

- The production of traditional Portland cement
- Blended cement (natural pozzolans)
- Cement where 100% of waste cement kiln dust is recycled into the kiln process
- Portland cement produced when cement kiln dust (CKD) is used to sequester a portion of the process related CO_2 emissions.

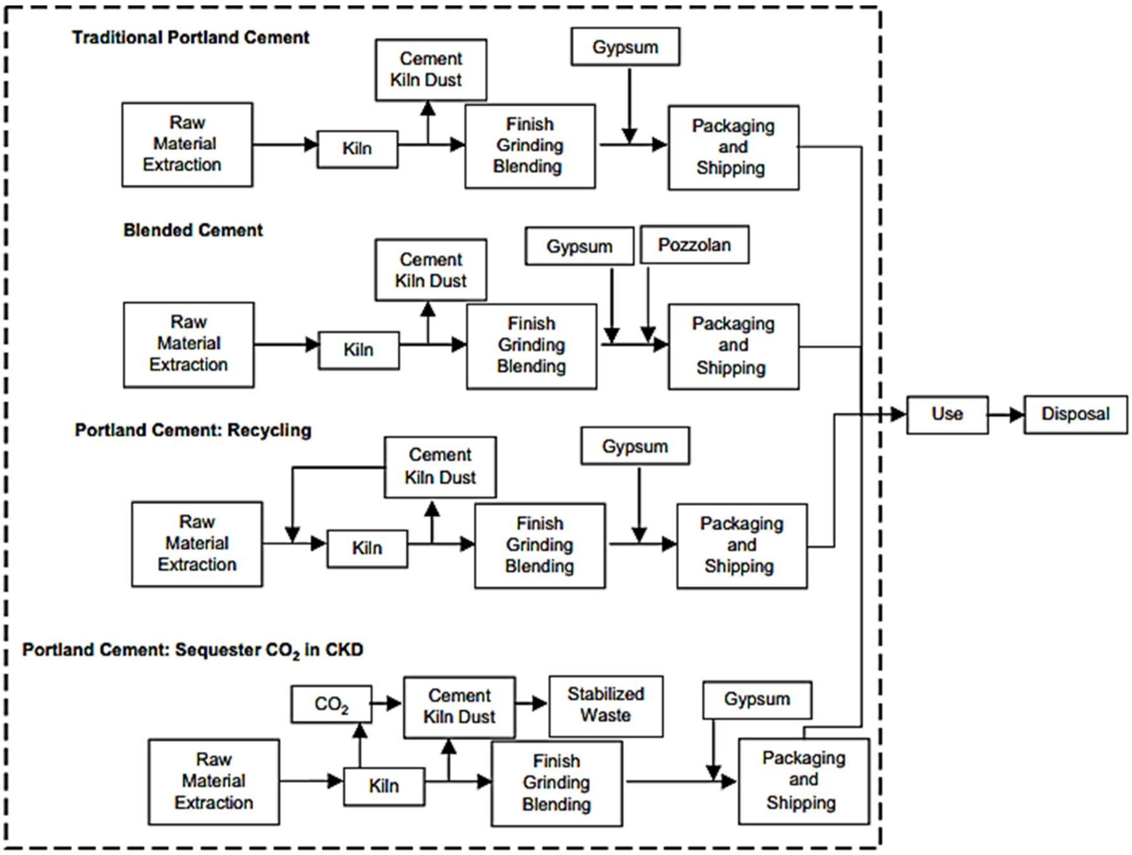

Figure 20: Scope of comparative LCA for cement manufacturing process. The dashed line signifies the boundaries of the system examined

As it can be seen in the previous Figure 20 the boundaries of the system include phases from raw material acquisition to packaging an shipping,

Analysis using SimaPro software shows that blended cements provide the greatest environmental savings (See Table 7) followed by utilization of CKD for sequestration. The recycling of CKD was found to have little environmental savings over the traditional process.

Table 7: Classification of process inputs and outputs for the four cements into environmental impact categories.

Environmental impact category	Traditional	Blended	Recycled CKD	CO_2 sequestration
Greenhouse	0.088	0.069	0.088	0.084
Acidification	0.043	0.034	0.043	0.043
Eutrophication	0.006	0.005	0.006	0.006
Heavy metals	0.204	0.161	0.204	0.204
Carcinogens	0.003	0.003	0.002	0.003
Winter smog	0.039	0.031	0.039	0.039
Summer smog	0.009	0.007	0.009	0.009
Energy resources	0.050	0.040	0.050	0.050

3.3 Discussion and comparison of the literature review

The previous articles have been selected in order to be taken as a reference in this LCA study. First of all it can be seen how system boundaries can change depending on the aim of the study. However, most of them have its limits in common (from raw materials acquisition to manufacturing and installation phases) as it is the model it will be followed.

Moreover, type and quantities of mix designs are changed in the different articles so it can be seen how the results also change depending on the scenario adopted and how Life Cycle Assessment is implemented in order to find the less impacting one. Particularly, the article (Deborah N. Huntzinger et al, 2009) is the one taken as a reference as the type of cements is the variable adopted and two of the four cements under study are the ones used in this thesis work.

Furthermore, when implementing Life Cycle Assessment different methods can be adopted as it was explained in Chapter 2. The article “Comparing the midpoint and endpoint approaches based on ReCiPe—a study of commercial buildings in Hong Kong” (Ya Hong Dong et al, 2015) has been chosen in order to show the different results obtained depending on the method. In addition to this, Recipe Midpoint method it is the one used in this study as it gives reliable data with low uncertainties, as it is also confirmed in (Jane C. Bare et al, 2000).

Life Cycle Assessment of reinforced concrete specimens

Several specimens with different geometries are chosen for the case study. Their LCA will be divided in four steps as it was said in Chapter 1: Goal and scope definition, LCI, LCIA and results and data interpretation.

4.1 Goal and scope definition

GOAL DEFINITION

Since nowadays reinforced concrete is the material mostly used in the sector of construction such as in buildings, bridges and roads, it seems necessary to make studies about its behavior when using different types and quantities of materials and also to evaluate its environmental impact. The idea is to make a comparison using different scenarios and finally conclude which is the most sustainable reinforced concrete structure under study. For this reason, LCA method has been adopted.

The different scenarios adopted follow several criteria, as changing the plants were the cement is produced and also changing the type of cement used always guaranteeing the same compression resistance, so their life phase will be the same for all of them.

SCOPE DEFINITION

When manufacturing a reinforced concrete specimen several processes are carried out, first the raw materials acquisition and its corresponding transportation, the mix design process, the installation, the maintenance and finally the repair, as it can be seen in Figure 21.

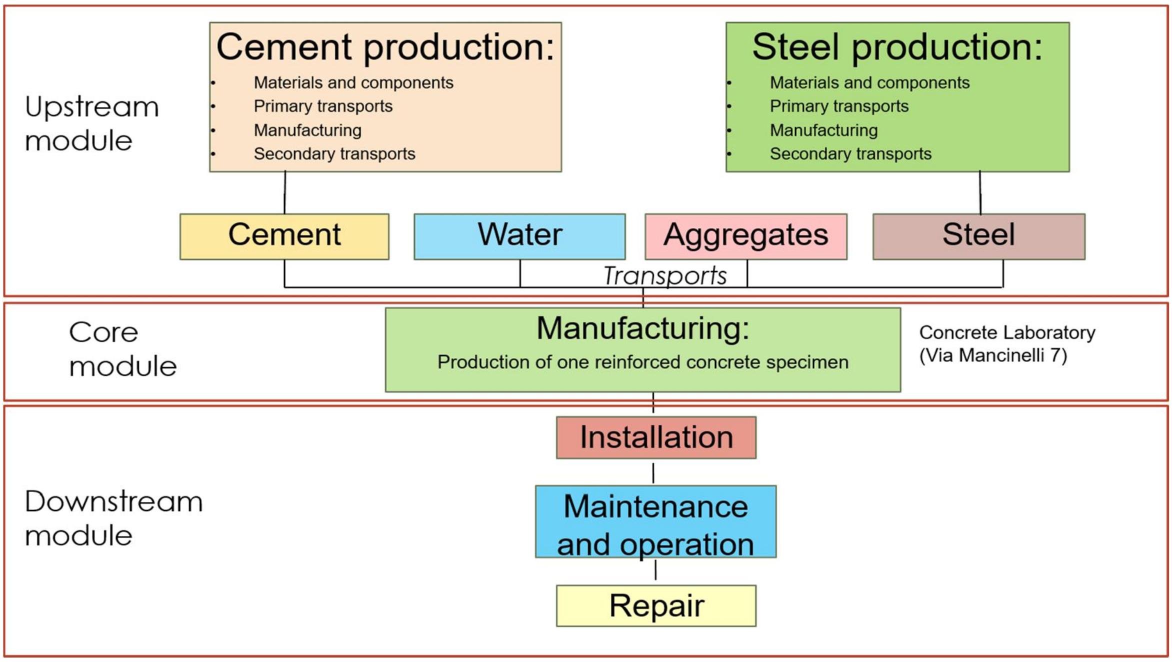

Figure 21: Product system of a cylindrical reinforced concrete specimen

However, system boundaries considered in this study only include the steps between raw materials acquisition and manufacturing of the product, Figure 22.

Note: In Figure 22 manufacturing includes mix design and installation processes

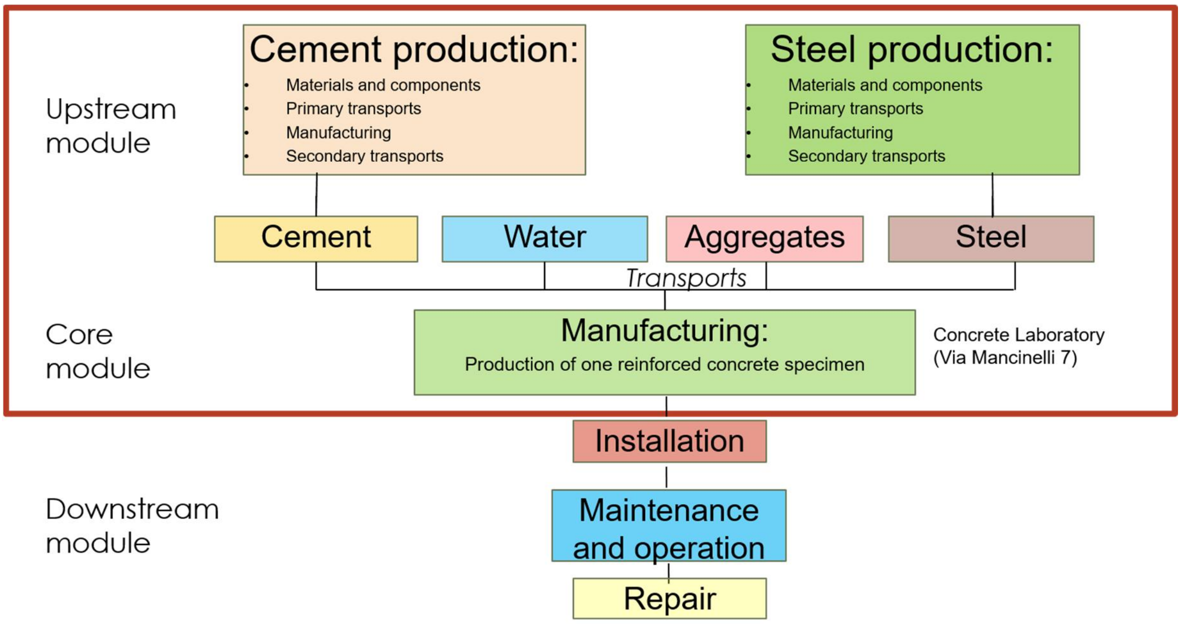

Figure 22: System boundaries of the product processes

The functional unit taken for the system is the manufacturing of one reinforced concrete specimen.

4.2 Data quality

Data collection has been made thanks to different articles and also from data extracted from the concrete laboratory so data can be divided into primary and secondary data:

4.2.2 PRIMARY DATA

As it was said in Chapter 1, it is data obtained from direct measurements. As the project is based on the specimens and machines reproduced and used in the *Concrete Laboratory, Via Mancinelli, Politecnico di Milano* all the data will be referred to it, then:

- Energy consumption of the mix design
- Energy consumption of the installation
- Steel transport
- Cement transport
- Aggregates transport

4.2.2 SECONDARY DATA

The secondary data used is:

- Amounts of materials used when performing the simulation of cylindrical specimens have been collected following several articles and reports of the Concrete Laboratory.
- The cement type emissions have been derived from the EPD (Environmental product declaration) provided by Buzzi Unicem.
- The average steel density value has been considered, 7850 kg/m^3.

The database used in this phase has been Ecoinvent, which provides all types of needed materials.

4.2.3 Performance-based durability design of reinforced concrete structures with stainless steel bars (M. Gastaldi, 2014)

Cylindrical reinforced specimens made by concrete and mortar and with different type and amounts of water and aggregates were subjected to tests in order to evaluate the statistical durability of the chloride threshold.

Results showed that this statistical distribution of the chloride threshold may be fitted by a betta distribution function as it can be seen in the following Figure 23:

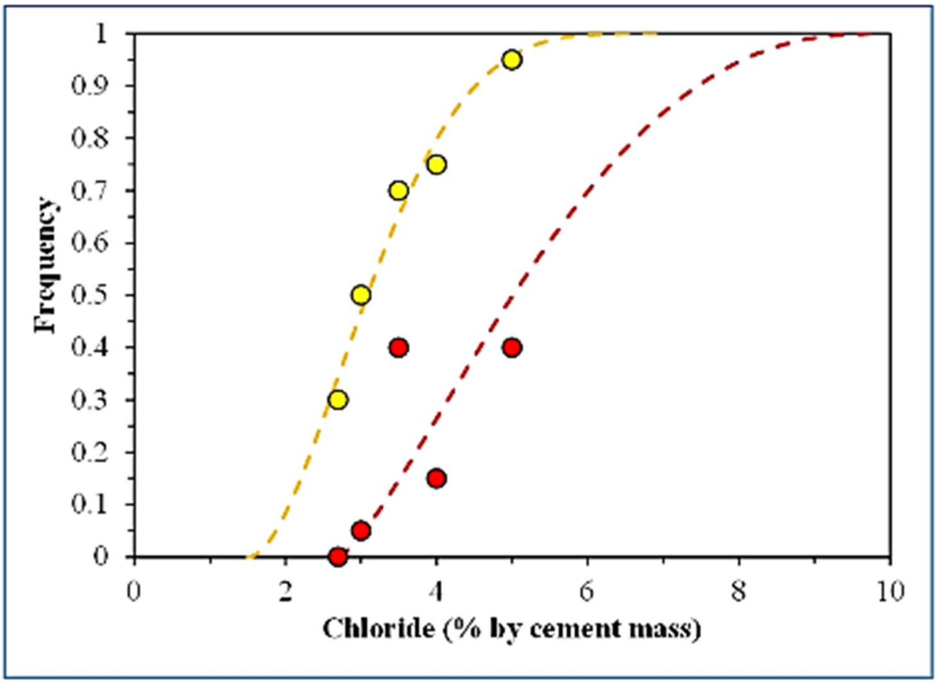

Figure 23: Cumulative probability distribution function of the steel

This article has been discussed because types and amounts of the materials have been useful for the simulation carried out in this thesis.

4.3 Life cycle Inventory

The previous data has been acquired doing an inventory research and finally the found information and values are the following:

4.3.1 Energy consumption of the mix design

Mix design is done in a concrete mixer which has a power of 0.15 kWh.

4.3.2 Energy consumption of the installation

Done on a vibrator table with a power of 0.055 kWh.

Both values of energy have been obtained from the concrete mixer and the vibrator table of the Concrete Laboratory from *Politecnico di Milano.*

Looking at the following Figure 24, it can be seen the value of kW consumed for the vibrator table, this value is 0.11 kW, which every 30 minutes (installation time) gives the value written before of 0.055 kWh.

Figure 24: Vibrator table energy consumption from the Concrete Laboratory, Politecnico di Milano

4.3.3 Steel transport:

Steel comes from *Valbruna Steelworks (Italy),* which is a leader in the production of *steel* and in the processing of stainless construction *steel* and metal alloys.

Valbruna distance to the *Concrete Laboratory* is about 199 km as can be seen in Figure 25:

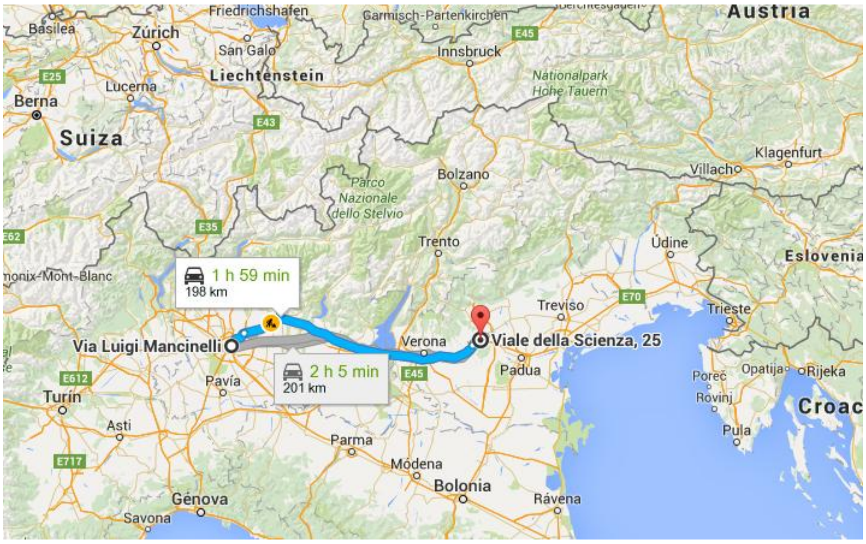

Figure 25: Distance from Via Luigi Mancinelli, Politecnico di Milano to Valbruna Steelworks (Viale della Scienza, 25, 36100 Vicenza VI, Italia)

This information about the supplier has been obtained from articles made by the Concrete Laboratory team and after confirmation of them.

4.3.4 Aggregates transport:

Crushed limestone aggregate comes from *Torrazza*, a supplier placed at 119 Km from the *Concrete Laboratory,* also information confirmed.

4.3.5 Cement type and transport:

The cement supplier is *Buzzi Unicem*, which is an active group in Italy in the production and distribution of cement, ready-mix concrete, natural aggregates and related products.

Data has been obtained by the EPD provided by *Buzzi Unicem,* which allowed considering different types of cements by means of their emissions to air and water in different plants all around Italy.

As the objective is to compare the environmental impacts of different reinforced concrete specimens having the same compression resistance, only cements of 42.5R type were considered, the EPD from *Buzzi Unicem* are shown in the following Table 8, Table 9 and Table 10:

Table 8: EPD impact indicators of different cements from different plants provided by Buzzi Unicem, part 1

7. Gli indicatori di impatto

	EMISSIONI GAS AD EFFETTO SERRA	DISTRUZIONE FASCIA D'OZONO	ACIDIFICAZIONE	EUTROFIZZAZIONE	FORMAZIONE OSSIDANTI FOTOCHIMICI	DISTRUZIONE RISORSE ABIOTICHE		RISORSE ENERGETICHE PRIMARIE RINNOVABILI NON UTILIZZATE COME MATERIE PRIME E TOTALI	RISORSE ENERGETICHE PRIMARIE NON RINNOVABILI NON UTILIZZATE COME MATERIE PRIME E TOTALI	COMBUSTIBILI SECONDARI RINNOVABILI	COMBUSTIBILI SECONDARI NON RINNOVABILI	SOSTITUZIONE CALORICA	RISORSE NON RINNOVABILI (MATERIE PRIME)	CONSUMO DI MATERIE SECONDE	POST CONSUMER - LEED	CONSUMO DI RISORSE IDRICHE	ENERGIA ELETTRICA DIRETTA	RIFIUTI NON PERICOLOSI	EMISSIONI DI POLVERI
	kg CO_2 eq	kg CFC_{11} eq E-8	kg SO_2 eq	kg PO_4^{3-} eq	kg C_2H_4 eq	kg Sb eq E-3	MJ	MJ	MJ	MJ	MJ	%	kg	kg	kg	m³	kWh	kg	kg
CEM I 42.5 R - Robilante	884	4.214	2,14	0,27	0,25	0,556	5.567	136	5.870	0	952	27,7	1.520	61,4	0	1,572	117	0	0,25
CEM I 52.5 R - Robilante	901	4.300	1,72	0,27	0,24	1,899	5.633	144	5.882	0	974	27,7	1.545	1,7	0	0,800	140	0	0,29
CEM II ALL 42,5 R - Robilante	831	3.994	2,21	0,26	0,25	0,607	5.315	179	5.637	0	884	27,7	1.487	86,4	0	2,027	110	0	0,24
CEM II BLL 32,5 R - Robilante	708	3.476	2,05	0,23	0,23	0,678	4.712	607	5.043	0	734	27,7	1.428	93,2	0	2,432	98	0,09	0,23
Robilante	**825**	**3.969**	**2,08**	**0,26**	**0,24**	**0,830**	**5.278**	**263**	**5.587**	**0**	**878**	**27,7**	**1.489**	**68,9**	**0**	**1,826**	**114**	**0,02**	**0,25**
CEM II ALL 42.5 R_Trino	820	4.254	1,82	0,28	0,25	1,696	5.354	146	5.611	0	859	0	1.515	37,9	0	1,272	88	0,02	0,27
CEM II BLL 32.5 R_Trino	677	3.655	1,64	0,24	0,22	1,435	4.563	99	4.800	0	692	0	1.430	40,1	0	1,268	75	0	0,25
CEM II BP 32.5 R_Trino	694	3.887	1,69	0,26	0,25	1,262	4.839	596	5.110	0	691	0	1.477	44,2	0	1,490	71	0,27	0,22
CEM IV A V 32.5 R_Trino	668	3.752	1,40	0,24	0,22	1,658	4.571	96	4.776	0	670	0	1.473	1,2	0	0,690	79	0	0,22
CEM IV A V 42.5 R_Trino	786	4.125	1,57	0,27	0,24	2,206	5.125	104	5.343	0	823	0	1.470	45,8	0	0,739	89	0	0,26
CEM IV B 32.5 R_Trino	637	3.413	1,29	0,22	0,20	2,088	4.216	85	4.399	0	661	0	1.170	247,6	0	0,622	72	0	0,23
Trino	**765**	**4.055**	**1,72**	**0,26**	**0,25**	**1,656**	**5.076**	**214**	**5.325**	**0**	**792**	**0**	**1.482**	**43,3**	**0**	**1,221**	**83**	**0,06**	**0,25**
CEM I 52.5 R_Vernasca	975	5.954	3,05	0,33	0,37	0,501	7.088	159	7.516	37	0	1,2	1.534	98,5	32	1,056	126	0	0,24
CEM II ALL 42.5 R_Vernasca	832	5.090	2,39	0,29	0,31	0,408	5.933	153	6.256	32	0	1,2	1.459	113,8	27	1,144	92	0,01	0,22
CEM II BLL 32.5 R_Vernasca	689	4.337	2,13	0,25	0,29	0,382	5.127	604	5.450	26	0	1,2	1.382	101,9	22	1,207	79	0,21	0,20
CEM IV A 32.5 R_Vernasca	732	4.875	2,08	0,28	0,30	0,382	5.492	106	5.779	27	0	1,2	1.382	139,5	23	0,836	81	0	0,18
CEM IV A 42.5 R_Vernasca	752	4.661	1,64	0,25	0,26	0,311	5.355	104	5.579	29	0	1,2	1.159	350,9	25	0,835	102	0	0,17
CEM IV B 32.5 R_Vernasca	649	4.203	1,84	0,24	0,26	3,139	4.794	96	5.246	5.048	24	1,2	1.089	352,2	21	0,720	77	0	0,24
Vernasca	**748**	**4.674**	**2,21**	**0,27**	**0,30**	**0,480**	**5.453**	**348**	**5.769**	**28**	**0**	**1,2**	**1.393**	**119,1**	**24**	**1,104**	**85**	**0,10**	**0,20**

Table 9: EPD impact indicators of different cements from different plants provided by Buzzi Unicem, part 2

9. Gli indicatori di impatto

	EMISSIONI GAS AD EFFETTO SERRA	DISTRUZIONE FASCIA D'OZONO	ACIDIFICAZIONE	EUTROFIZZAZIONE	FORMAZIONE OSSIDANTI FOTOCHIMICI	DISTRUZIONE RISORSE ABIOTICHE		RISORSE ENERGETICHE PRIMARIE RINNOVABILI NON UTILIZZATE COME MATERIE PRIME E TOTALI	RISORSE ENERGETICHE PRIMARIE NON RINNOVABILI NON UTILIZZATE COME MATERIE PRIME E TOTALI	COMBUSTIBILI SECONDARI RINNOVABILI	COMBUSTIBILI SECONDARI NON RINNOVABILI	SOSTITUZIONE CALORICA	RISORSE NON RINNOVABILI (MATERIE PRIME)	CONSUMO DI MATERIE SECONDE	POST CONSUMER - LEED	CONSUMO DI RISORSE IDRICHE	ENERGIA ELETTRICA DIRETTA	RIFIUTI NON PERICOLOSI	EMISSIONI DI POLVERI
	kg CO_2 eq	kg CFC_{11} eq E-8	kg SO_2 eq	kg PO_4^{3-} eq	kg C_2H_4 eq	kg Sb eq E-3	MJ	MJ	MJ	MJ	MJ	%	kg	kg	kg	m³	kWh	kg	kg
CEM II A-LL 42.5 R_Settimello	974	7.013	3,23	0,38	0,41	0,637	7,983	167	8.411	0	0	0	1.675	12,1	0	1,139	140	0	0,24
CEM II B-LL 32.5 R_Settimello	832	6.011	2,88	0,33	0,36	0,557	6.875	149	7.262	0	0	0	1.578	10,3	0	0,981	122	0	0,22
CEM III A 32.5 N_Settimello	578	4.431	2,78	0,25	0,29	0,465	5.248	156	5.672	0	0	0	890	501,7	0	0,771	122	0	0,15
CEM IV B V 32.5 R_Settimello	756	5.558	2,78	0,31	0,34	0,530	6.351	140	6.732	0	0	0	1.214	330,3	0	0,913	110	0	0,18
Settimello	**843**	**6.126**	**2,96**	**0,34**	**0,37**	**0,571**	**7.001**	**153**	**7.402**	**0**	**0**	**0**	**1.459**	**138,8**	**0**	**1,002**	**125**	**0**	**0,21**
CEM I 52.5 R_Guidonia	983	6.426	2,82	0,33	0,34	1,213	7.551	163	7.867	0	0	0	1.639	13,2	0	0,963	160	0	0,21
CEM II A-LL 42.5 R_Guidonia	885	5.803	2,75	0,30	0,32	1,193	6.821	214	7.176	0	0	0	1.583	15,8	0	0,970	139	0,02	0,23
CEM II B-LL 32.5 R_Guidonia	737	4.845	2,31	0,26	0,27	1,126	5,736	404	6.049	0	0	0	1.489	9,7	0	0,827	119	0	0,22
CEM IV A 42.5 R_Guidonia	790	5.169	1,83	0,26	0,26	1,018	5.993	120	6.217	0	0	0	1.529	10,8	0	0,810	131	0	0,19
CEM IV B 32.5 R_Guidonia	658	4.359	2,10	0,23	0,24	0,960	5.182	315	5.473	0	0	0	1.469	8,6	0	0,733	116	0,07	0,17
Guidonia	**800**	**5.257**	**2,47**	**0,28**	**0,29**	**1,134**	**6.198**	**296**	**6.525**	**0**	**0**	**0**	**1.533**	**12,4**	**0**	**0,881**	**129**	**0,06**	**0,22**
CEM I 52.5 R_Barletta	969	4.437	3,25	0,28	0,31	0,444	5.632	202	6.132	0	1.576	45,6	1.628	6,3	0	0,826	164	0	0,24
CEM II A-LL 42.5 R_Barletta	825	3.786	2,68	0,24	0,27	0,377	4.764	303	5.180	0	1.348	45,6	1.547	10,6	0	0,893	128	0,00	0,22
CEM II B-LL 32.5 R_Barletta	722	3.339	2,51	0,21	0,24	0,341	4.253	154	4.640	0	1.166	45,6	1.473	10,2	0	0,739	122	0	0,21
CEM IV B 32.5 R_Barletta	637	3.173	2,34	0,21	0,24	0,329	4.089	869	4.493	0	972	45,6	1.462	3,9	0	0,808	122	0,09	0,17
Barletta	**771**	**3.598**	**2,60**	**0,23**	**0,26**	**0,362**	**4.560**	**357**	**4.971**	**0**	**1.242**	**45,6**	**1.519**	**8,9**	**0**	**0,846**	**127**	**0,02**	**0,20**
CEM I 42.5 R_Augusta	914	5.723	1,89	0,32	0,29	1,715	6.482	98	6.682	0	0	0	1.666	0,2	0	0,856	102	0	0,24
CEM I 52.5 R_Augusta	940	5.936	1,99	0,33	0,30	1,718	6.811	124	7.046	0	0	0	1.672	0,2	0	0,932	135	0	0,25
CEM II A-LL 42.5 R_Augusta	828	5.218	1,81	0,29	0,27	1,739	5.963	100	6.169	0	0	0	1.607	11,5	0	1,037	103	0	0,24
CEM II B-LL 32.5 R_Augusta	710	4.493	1,59	0,25	0,25	1,696	5.205	602	5.416	0	0	0	1.535	10,7	0	1,104	84	0,09	0,23
CEM IV A 42.5 R_Augusta	791	5.025	1,67	0,28	0,26	1,642	5.726	112	5.919	0	0	0	1.593	0,2	0	0,773	103	0	0,21
CEM IV B 32.5 R_Augusta	654	4.187	1,40	0,23	0,21	1,745	4.752	80	4.912	0	0	0	1.494	0,1	0	0,650	83	0	0,19
Augusta	**794**	**5.019**	**1,72**	**0,28**	**0,26**	**1,698**	**5.749**	**251**	**5.953**	**0**	**0**	**0**	**1.589**	**6,3**	**0**	**0,955**	**99**	**0,03**	**0,23**

Table 10: EPD impact indicators of different cements from different plants provided by Buzzi Unicem, part 3

10. Gli indicatori di impatto

	EMISSIONI GAS AD EFFETTO SERRA	DISTRUZIONE FASCIA D'OZONO	ACIDIFICAZIONE	EUTROFIZZAZIONE	FORMAZIONE OSSIDANTI FOTOCHIMICI	DISTRUZIONE RISORSE ABIOTICHE		RISORSE ENERGETICHE PRIMARIE RINNOVABILI NON UTILIZZATE COME MATERIE PRIME E TOTALI	RISORSE ENERGETICHE PRIMARIE NON RINNOVABILI NON UTILIZZATE COME MATERIE PRIME E TOTALI	COMBUSTIBILI SECONDARI RINNOVABILI	COMBUSTIBILI SECONDARI NON RINNOVABILI	SOSTITUZIONE CALORICA	RISORSE NON RINNOVABILI (MATERIE PRIME)	CONSUMO DI MATERIE SECONDE	POST CONSUMER - LEED	CONSUMO DI RISORSE IDRICHE	ENERGIA ELETTRICA DIRETTA	RIFIUTI NON PERICOLOSI	EMISSIONI DI POLVERI
	kg CO_2 eq	kg CFC_{11} eq E-8	kg SO_2 eq	kg PO_4^{3-} eq	kg C_2H_4 eq	kg Sb eq E-3	MJ	MJ	MJ	MJ	MJ	%	kg	kg	kg	m³	kWh	kg	kg
CEM I 52.5 R_Siniscola	1.004	6.448	2,14	0,34	0,30	0,078	7.490	168	7.786	0	0	0	1.550	48,9	0	0,998	190	0	0,24
CEM II ALL 42.5 R_Siniscola	872	5.658	1,86	0,31	0,27	0,082	6.507	142	6.757	0	0	0	1.489	45,0	0	0,875	148	0	0,23
CEM IV A V 32.5 R_Siniscola	758	5.003	1,67	0,28	0,26	0,089	5.800	646	6.056	0	0	0	1.204	280,6	0	0,972	130	0	0,19
Siniscola	**799**	**5.242**	**1,74**	**0,29**	**0,26**	**0,087**	**6.066**	**502**	**6.323**	**0**	**0**	**0**	**1.290**	**212,8**	**0**	**0,951**	**138**	**0,09**	**0,20**
CEM I	**915**	**4.943**	**2,09**	**0,29**	**0,27**	**1,251**	**6.100**	**136**	**6.381**	**1,8**	**597**	**-**	**1.580**	**26**	**1,6**	**1,082**	**129**	**0**	**0,25**
CEM II	**784**	**4.574**	**2,21**	**0,27**	**0,27**	**0,925**	**5.520**	**321**	**5.833**	**6,3**	**381**	**-**	**1.500**	**48**	**5,4**	**1,224**	**104**	**0,06**	**0,23**
CEM III	**578**	**4.431**	**2,78**	**0,25**	**0,29**	**0,465**	**5.248**	**156**	**5.672**	**0**	**0**	**-**	**890**	**502**	**0,0**	**0,771**	**122**	**0**	**0,15**
CEM IV	**731**	**4.546**	**1,92**	**0,26**	**0,26**	**1,040**	**5.312**	**266**	**5.579**	**4,8**	**208**	**-**	**1.414**	**95**	**4,1**	**0,801**	**105**	**0,03**	**0,19**
BUZZI UNICEM	**787**	**4.605**	**2,14**	**0,27**	**0,27**	**0,979**	**5.537**	**291**	**5.838**	**5,5**	**368**	**14,8**	**1.490**	**56**	**4,7**	**1,127**	**107**	**0,05**	**0,22**
BUZZI UNICEM – (A1 – A2)	**153**	**4.605**	**1,58**	**0,13**	**0,22**	**0,979**	**5.537**	**291**	**5.838**	**6**	**1**	**0**	**1.490**	**27**	**4,7**	**1,119**	**0**	**0,00**	**0,22**
BUZZI UNICEM – (A3)	**634**	**0,27**	**0,56**	**0,14**	**0,05**	**0,000003**	**0,36**	**0,0013**	**0,358**	**0,0**	**367**	**14,8**	**0**	**29**	**0**	**0,008**	**107**	**0,005**	**0,01**
BUZZI UNICEM – OT. GENERIC (%)	**0,4%**	**0,7%**	**2,1%**	**1,1%**	**1,7%**	**7,4%**	**1,1%**	**0,5%**	**1,2%**	**0%**	**0%**	**0%**	**9,3%**	**0%**	**0%**	**4,5%**	**0%**	**0%**	**5,3%**

Moreover, the average composition is summarized in the following Table 11:

Table 11: Average composition for all cements

PRODUCTS FOR NATURAL RESOURCES	Percentage
Limestone	65.4 %
Clay	16.5 %
Marl	6.7 %
Gypsum	1.2 %
Pozzolan	2.9 %
Silica Sand	1.1 %
Steel minerals	0.8 %
Other raw materials	0.6 %
PRODUCTS	
Matrix, Urea, ferrous sulfate, additives	3.2 %
RECOVERED WASTE	1.6 %

Example:
In order to do the simulation it has to be taken into account that the different substances emitted to the atmosphere contribute to different categories, for example the CO_2 contributes both for global warming and the distribution of the ozone layer. The correct value of CO_2 kg eq will be then obtained by finding in Simapro the factor of CMC_{11} that contributes, for that characterization must be applied.
For example for the CEM II ALL 42.5R in Trino Plant the correct value of CO_2 kg eq will be obtained in this way:

$$820\ kg\ CO_2 \ = 1 \cdot CO_2\ kg\ eq + 4750\ CFC_{11}\ kg\ eq$$

where 1 and 4750 are both the factors for global warming and the distribution ozone layer. By looking at the table that the kg eq of CFC_{11} is $4.258 \cdot 10^{-5}$ we can get the value of CO_2 kg and it is ready to insert it in the cement sheet in SimaPro.
The same must be done for all categories.

In conclusion, the type of cements used are CEM II ALL (Portland-limestone), CEM I (Portland cement, reference one), CEM II ALL (Portland-limestone) and CEM IV A V

(Pozzolanic cement) and their impacts are taken in the plants of Robilante, Trino, Vernasca, Settimelo, Barletta, Guidonia, Augusta and Siniscola.
A general idea of where they are placed is illustrated in the following Figure 26:

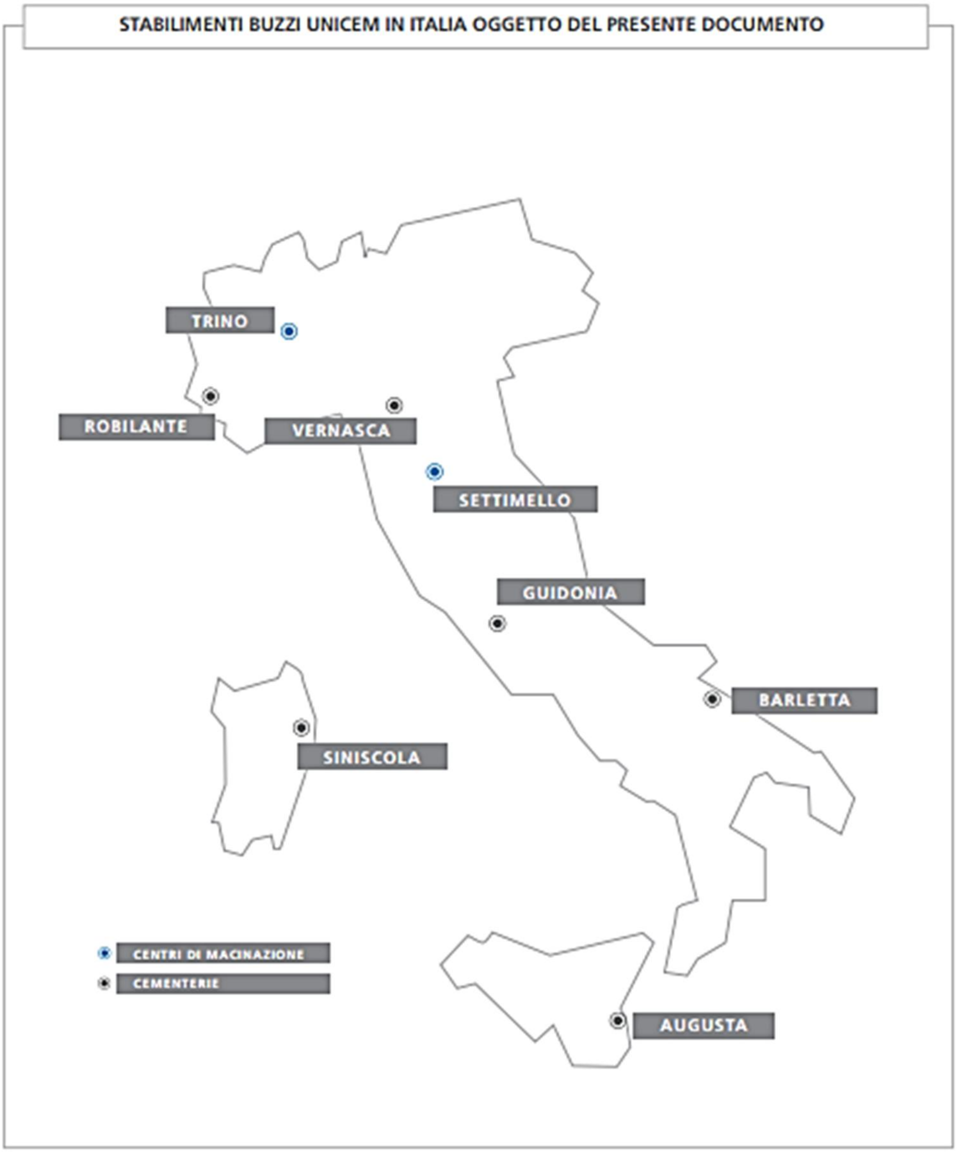

Figure 26: Buzzi Plants distribution over Italy

The simulations will be done on a very simple cylindrical bar specimen and also on a more complex structure with different geometry so the volumes and the amounts of materials will be different as it will be explained.

4.3.6 Data amounts on the cylindrical bar specimen

This data has been taken from *Performance-based durability design of reinforced concrete structures with stainless Steel* article, the amounts are shown in Table 12:

Table 12: Amounts of the fresh concrete mix taken from the article Performance-based durability design of reinforced concrete structures with stainless Steel

CONCRETE	**kg/m^3**
Cement	400
Water	200
Crushed limestone aggregate	1704

As the amounts are needed in terms of grams, the geometry of the cylindrical specimen is needed and it is also taken from the article:

"Specimens were cylinders with diameter of 75 mm and height of 100 mm, with a 20 mm diameter stainless steel reinforcing bar along the axis. The two ends of each bar, before casting, were masked with a styrene-butadiene-modified cement mortar and coated with a heat shrinkable sleeve; a length of the bar of 60 mm was exposed to the concrete."

So the resulting geometry considered is represented in Figure 27:

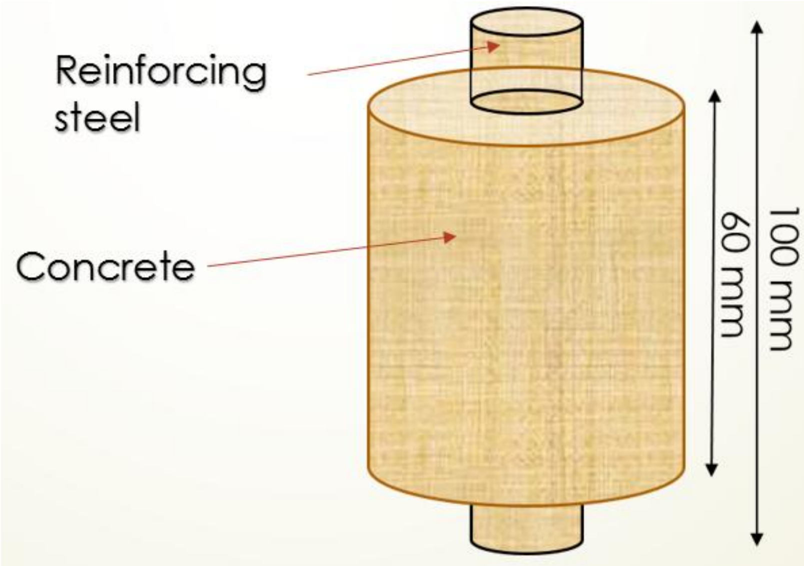

Figure 27: Cylindrical reinforced concrete specimen

Then the volume of concrete and steel are calculated and finally the amounts can be obtained (See Table 13 and Table 14).

Table 13: Concrete and steel volumes of the simple geometry

Material	Volume (mm^3)
Reinforcing steel	31416
Concrete	265072

Table 14: Amounts of materials used for the simulation for a cylinder reinforced concrete specimen bar

Material	Amount (g)
Cement	106
Deionized water	53
Crushed limestone aggregate	452
Reinforcing steel	247

4.3.7 Data amounts on a more complex structure

Data and scheme provided by the Concrete Laboratory based on previous experiments is showed in Figure 28:

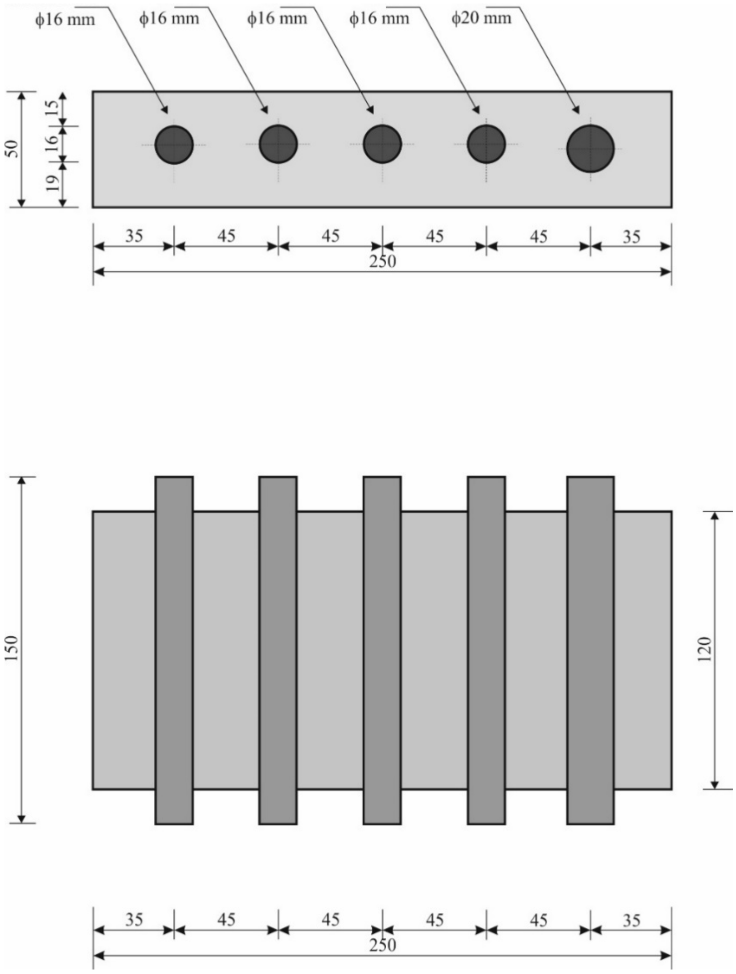

Figure 28: Geometrical dimensions of the reinforcing concrete structure

Calculating the volumes of concrete and steel the amounts can be also calculated as in the previous case (See Table 15 and Table 16).

Table 15: Volumes of concrete and steel for the complex geometry

Material	Volume (mm^3)
Reinforcing steel	167761
Concrete	1365791.192

Table 16: Amounts of materials used for the simulation the complex reinforced concrete structure

Material	Amount (g)
Cement	546.31
Deionized water	273.158
Crushed limestone aggregate	2327.30
Reinforcing steel	1316.916

In the following Table 17 it is summarized all the primary and secondary data collected to the elaboration of the simulation as well as the data that will be changed during it.

Table 17: Data used during the LCA simulation analysis

Variable	Value/ type	Comments
Energy mix design consumption	0.15 kWh (Italian current)	Machines from Concrete Lab
Energy installation consumption	0.055 kW (Italian current)	Machines from Concrete Lab
Steel transport	199 km	Valbruna supplier
Cement transport		Buzzi Unicem supplier Depends on the scenario
Aggregates transport	119 km	Torrazza
Cement type and amount		Depends on the scenario
Steel type and amount	Reinforcing steel	Amount depends on the scenario
Water type and amount	Deionized water	Amount depends on the scenario
Aggregates type and amount	Crushed limestone	Amount depends on the scenario
Concrete volume		Depends on the scenario
Reinforcing steel bar dimension		Depends on the scenario
Steel density	7850 kg/m^3	

4.4 Life Cycle Inventory Assessment

4.4.1 SimaPro software

SimaPro is the software used to develop the simulation, several hypothesis has been considered in relation to the data and processes:

- All transports have been made in a *Transport, freight, lorry 16-32 metric ton, EURO4 {RER}, Alloc Rec, U* and *Ferry, transoceanic ship, EURO4 {RER}, Alloc Rec, U*
- As the simulation is made in Italy electricity considered has been *Electricity, medium voltage, Alloc Rec, U {IT}.*
- All materials data is referred to global values {GLO}.
- Energy considered in the manufacturing phase is the sum of mix design energy and installation energy.

4.4.2 SimaPro simulation scheme

In order to perform the simulation, three main processes have been created in SimaPro Software (See Figure 29):

1. Materials and components process: it involves all the materials used for the manufacturing of the specimen (sand, aggregates, cement and steel).
2. Primary transports: all materials transport distances have been added to this process.
3. Manufacturing (Laboratory): it includes values of energy for both the mix design and the installation of the specimen.

Global impacts made by each process can be now analyzed.

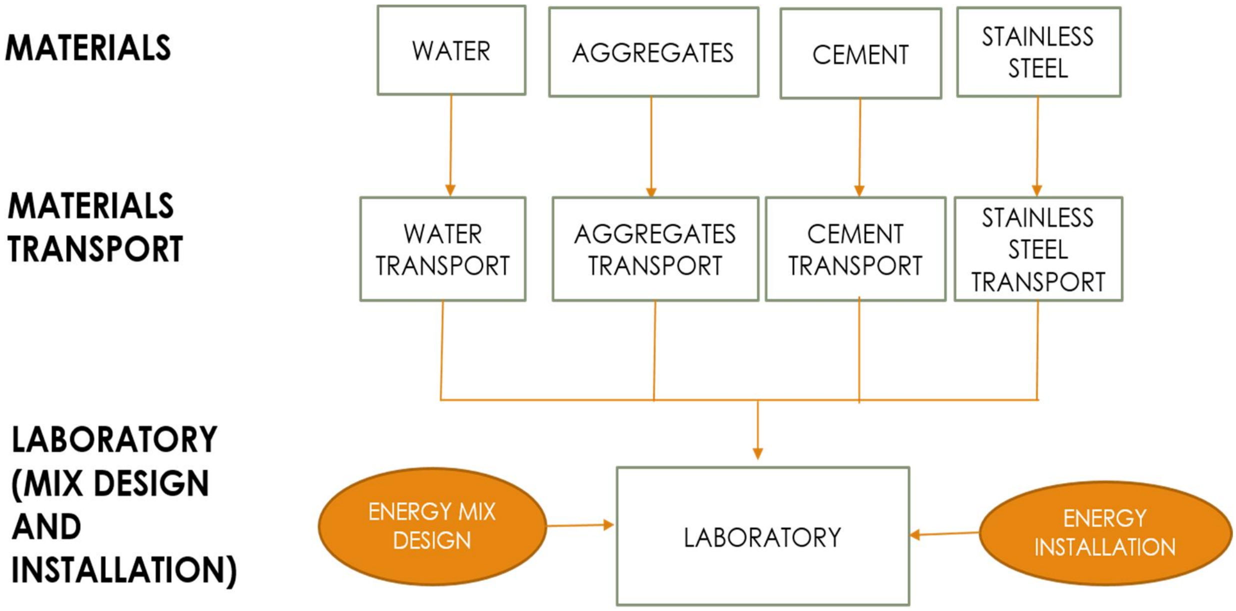

Figure 29: Three main processes developed in SimaPro in order to analyze global impacts of the reinforced concrete structures

Results and discussion

As it was previously said the simulation is developed on two different reinforced concrete structures, one simply cylindrical and another one more complex but always following the same way of performance.

The comparison of results is done in two different ways, the first one changing the cement keeping constant the supplier plant where it is produced and the second one changing the plant keeping constant the type of cement.

5.1 Life cycle analysis of a cylindrical reinforced concrete structure

Data that has been kept constant is summarized in the following Table 18:

Table 18: Constant data used for the simulation of a cylindrical reinforced concrete bar specimen

Variable	Value	Comments
Energy mix design consumption	0.15 kWh	Concrete Lab machines
Energy installation consumption	0.055 kWh	
Steel transport	199 km	Valbruna supplier
Aggregates transport	119 km	Torrazza
Cement amount	106.02 g	
Steel type and amount	246.61 g	Reinforcing steel
Water type and amount	53.01 g	Deionized water
Aggregates type and amount	451.68 g	Crushed limestone
Concrete cover thickness	55 mm	
Concrete height	60 mm	
Reinforcing steel diameter	20 mm	
Reinforcing steel height	100 mm	
Steel density	7850 kg/m^3	

IDEAL CASE

First of all, it will be analyzed the case in which it is considered CEM I (Portland cement) and a plant which is not too far from the Laboratory of concrete in Via Mancinelli, for example Robilante.

In this way it can be showed the general behavior of all the simulations for all cements and plants (previously simulated and confirmed), which is the phase more impacting and why.

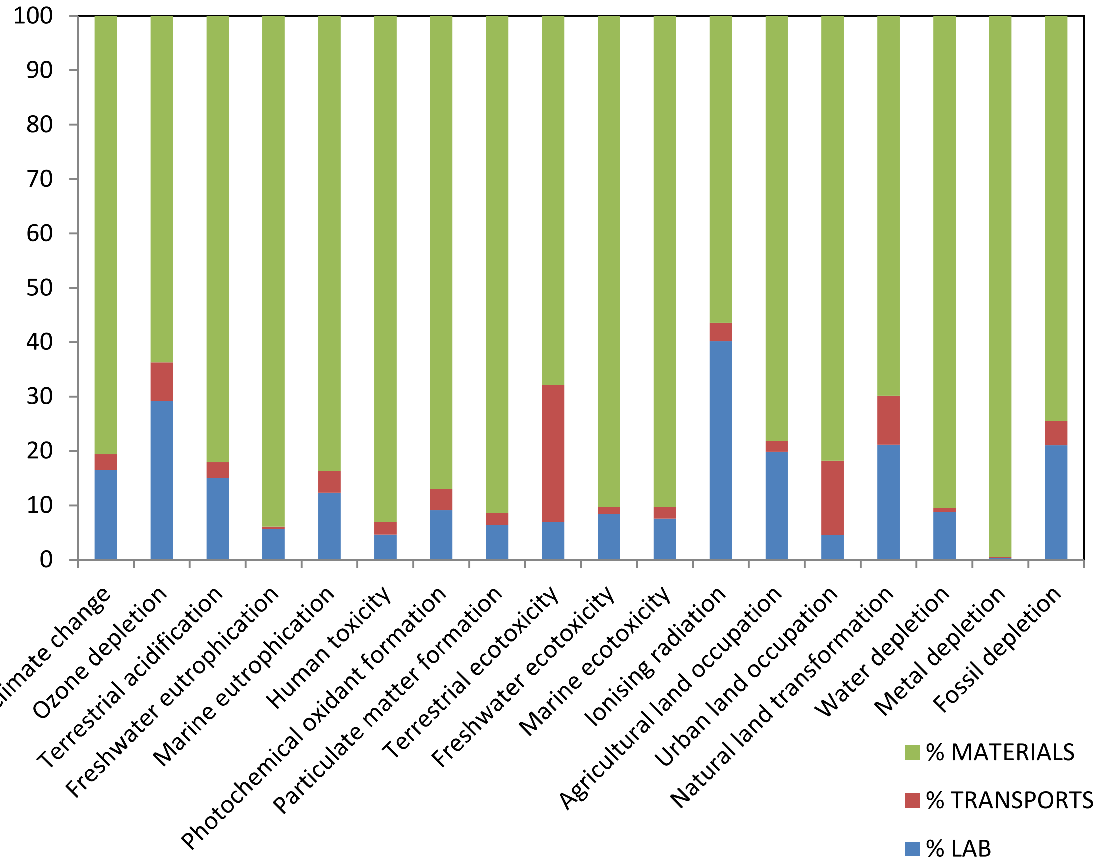

Figure 30: Environmental impacts using CEM I produced in Robilante plant

From Figure 30 and Table 19 it can be seen that the materials phase is the more impacting one (from 56 to 99% in all cathegories), especially in metal depletion, which takes the biggest value. Focusing on this category it is possible to see the process contributions which gives such a big value.

Table 19: Percentage values of environmental impacts using CEM I produced in Robilante Plant.

	CEM I		
Impact category	% MATERIALS	% TRANSPORTS	% LAB
Climate change	80.62	2.89	16.49
Ozone depletion	63.72	7.08	29.20
Terrestrial acidification	82.09	2.87	15.04
Freshwater eutrophication	93.87	0.45	5.68
Marine eutrophication	83.73	3.92	12.35
Human toxicity	93.04	2.31	4.65
Photochemical oxidant formation	86.98	3.89	9.13
Particulate matter formation	91.45	2.15	6.40
Terrestrial ecotoxicity	67.84	**25.20**	6.96
Freshwater ecotoxicity	90.24	1.37	8.39
Marine ecotoxicity	90.30	2.14	7.56
Ionising radiation	56.44	3.38	**40.18**
Agricultural land occupation	78.19	1.93	19.88
Urban land occupation	81.79	13.63	4.58
Natural land transformation	69.86	8.99	21.15
Water depletion	90.50	0.69	8.81
Metal depletion	**99.49**	0.18	0.33
Fossil depletion	74.50	4.46	21.04

Table 20: Process contributions for the category metal depletion

Process	Unity	Total	MATERIALS, CEM II ALL 42.5R	MATERIALS, CEM I 42.5R
Total of all processes	kg Fe eq	0.4946	0.4924	0.4916
Other processes	kg Fe eq	0.0079	0.0074	0.0022
Iron ore, crude ore, 46% Fe {GLO}| iron mine operation, crude ore, 46% Fe | Alloc Rec, U	kg Fe eq	0.2498	0.24903961	0.2490
Manganese concentrate {GLO}| production | Alloc Rec, U	kg Fe eq	0.0882	0.0879	0.0879
Ferronickel, 25% Ni {GLO}| production | Alloc Rec, U	kg Fe eq	0.0741	0.0739	0.0739
Chromite ore concentrate {GLO}| production | Alloc Rec, U	kg Fe eq	0.0408	0.0406	0.0406
Iron ore, beneficiated, 65% Fe {CA-QC}| iron mine operation and iron ore beneficiation to 65% Fe | Alloc Rec, U	kg Fe eq	0.0115	0.0115	0.0115
Molybdenite {GLO}| mine operation | Alloc Rec, U	kg Fe eq	0.0090	0.0090	0.0090
Molybdenite {RLA}| copper mine operation | Alloc Rec, U	kg Fe eq	0.0070	0.0070	0.0070
Molybdenite {RNA}| copper mine operation | Alloc Rec, U	kg Fe eq	0.0060	0.0059	0.0059

Furthermore, the Table 19 of percentages shows a quite difference regarding the laboratory phase in ionizing radiation in comparison with the other categories (between 0 and 29%) being its average of about 40.16%.

As it can be seen in the following Table 21 of process contribution in each category it is mostly due to the high voltage electricity in the pressure water reactor and to the uranium mine operation for nuclear energy production.

Table 21: Process contributions for the category ionizing radiation

Process	Unity	Total	LABORATORY, CEM II ALL 42.5 R	LABORATORY, CEM I 42.5
Total of all processes	kBq U235 eq	4.10E-02	1.51E-02	1.51E-02
Other processes	kBq U235 eq	1.60E-03	2.12E-04	2.12E-04
Electricity, high voltage {CH}| electricity production, nuclear, boiling water reactor | Alloc Rec, U	kBq U235 eq	1.52E-03	1.36E-03	1.36E-03
Electricity, high voltage {CH}| electricity production, nuclear, pressure water reactor | Alloc Rec, U	kBq U235 eq	2.85E-04	2.56E-04	2.56E-04
Electricity, high voltage {GB}| electricity production, nuclear, boiling water reactor | Alloc Rec, U	kBq U235 eq	3.58E-04	1.02E-05	1.02E-05
Electricity, high voltage {RFC}| electricity production, nuclear, boiling water reactor | Alloc Rec, U	kBq U235 eq	2.81E-04	7.57E-06	7.57E-06
Electricity, high voltage {RU}| electricity production, nuclear, boiling water reactor | Alloc Rec, U	kBq U235 eq	4.53E-04	1.47E-04	1.47E-04
Electricity, high voltage {SE}| electricity production, nuclear, boiling water reactor | Alloc Rec, U	kBq U235 eq	3.16E-04	8.95E-06	8.95E-06
Electricity, high voltage {SERC}| electricity production, nuclear, boiling water reactor | Alloc Rec, U	kBq U235 eq	2.89E-04	7.78E-06	7.78E-06
Electricity, high voltage {WECC, US only}| electricity production, nuclear, boiling water reactor | Alloc Rec, U	kBq U235 eq	1.28E-04	3.46E-06	3.46E-06
Low level radioactive waste {CH}| treatment of, plasma torch incineration | Alloc Rec, U	kBq U235 eq	8.52E-03	1.49E-03	1.49E-03
Spent nuclear fuel {RoW}| treatment of, reprocessing | Alloc Rec, U	kBq U235 eq	4.40E-03	1.65E-03	1.65E-03
Tailing, from uranium milling {GLO}| treatment of | Alloc Rec, U	kBq U235 eq	2.23E-02	9.76E-03	9.76E-03
Uranium ore, as U {RNA}| uranium mine operation, underground | Alloc Rec, U	kBq U235 eq	2.72E-04	1.19E-04	1.19E-04
Uranium ore, as U {RoW}| uranium mine operation, underground | Alloc Rec, U	kBq U235 eq	2.57E-04	1.12E-04	1.12E-04

Table 22: Process contributions for the category terrestrial ecotoxicity

Process	Unity	Total	TRANSPORTS, CEM II ALL 42.5R	TRANSPORTS, CEM I 42.5 R
Total of all processes	kg 1,4-DB eq	6.13E-05	1.62E-05	1.62E-05
Other processes	kg 1,4-DB eq	1.17E-05	8.35E-07	8.37E-07
Brake wear emissions, lorry {RoW}| treatment of | Alloc Rec, U	kg 1,4-DB eq	1.78E-05	1.03E-05	1.03E-05
Steel, low-alloyed {RoW}| steel production, electric, low-alloyed | Alloc Rec, U	kg 1,4-DB eq	9.41E-06	1.00E-08	1.00E-08
Brake wear emissions, lorry {RER}| treatment of | Alloc Rec, U	kg 1,4-DB eq	7.21E-06	**4.19E-06**	**4.19E-06**
Ferronickel, 25% Ni {GLO}| production | Alloc Rec, U	kg 1,4-DB eq	4.00E-06	4.47E-09	4.46E-09
Steel, low-alloyed {RER}| steel production, electric, low-alloyed | Alloc Rec, U	kg 1,4-DB eq	3.42E-06	3.65E-09	3.64E-09
Sinter, iron {GLO}| production | Alloc Rec, U	kg 1,4-DB eq	2.91E-06	4.51E-09	4.50E-09
Natural gas, unprocessed, at extraction {GLO}| production | Alloc Rec, U	kg 1,4-DB eq	1.67E-06	9.64E-09	9.97E-09
Tyre wear emissions, lorry {RoW}| treatment of | Alloc Rec, U	kg 1,4-DB eq	1.38E-06	**8.02E-07**	**8.02E-07**
Rape seed, Swiss integrated production {CH}| rape seed production, Swiss integrated production, intensive | Alloc Rec, U	kg 1,4-DB eq	1.00E-06	2.45E-09	2.11E-09
Electricity, high voltage {IT}| heat and power co-generation, oil | Alloc Rec, U	kg 1,4-DB eq	8.39E-07	2.82E-10	2.35E-10

Moreover, the transport phase ranges generally from 0 to 14% and only in terrestrial ecotoxicity it is also high being its average of about 25%. The reasons are mainly the brake wear emissions and the tyre wear emissions in the lorry, as shown in Table 22.

On the other hand, it it can be seen from Figure 30 and Table 19 that the laboratory phase for this simple geometry plays an important role ranging from 0.33 to 40%. In the following Figure 31 it is compared the laboratory phase changing the energy of the mix design and installation as the specimen was made in Italy, Spain and the United States. The aim of this comparison is to check if such high values in laboratory phase seen in Figure 30 are because of the electricity used in Italy.

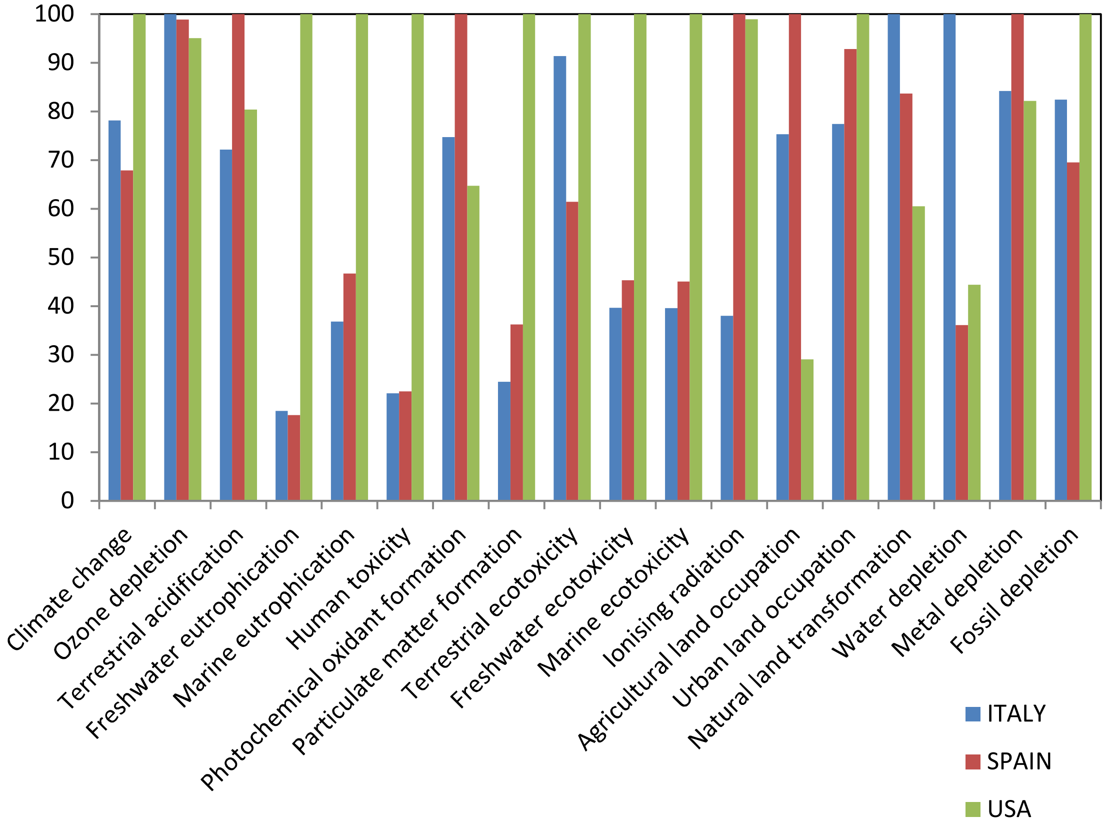

Figure 31: Reduction values comparison of laboratory impacts for CEM I produced in Robilante plant in Italy, Spain and USA for a simple geometry

As it can be seen comparing the three reduction values for each category, italian electricity is not responsible of such high laboratory values as the US electricity gives the higher environmental impacts almost in all categories. Regarding italian and spanish electricity, they present differences on the labobratory phase depending on the category being them almost negligible in comparison with the US electricity, which is reasonable as US electricity uses a large value of hard coal as it can be seen in the following Figure 32, Figure 33 and Figure 34:

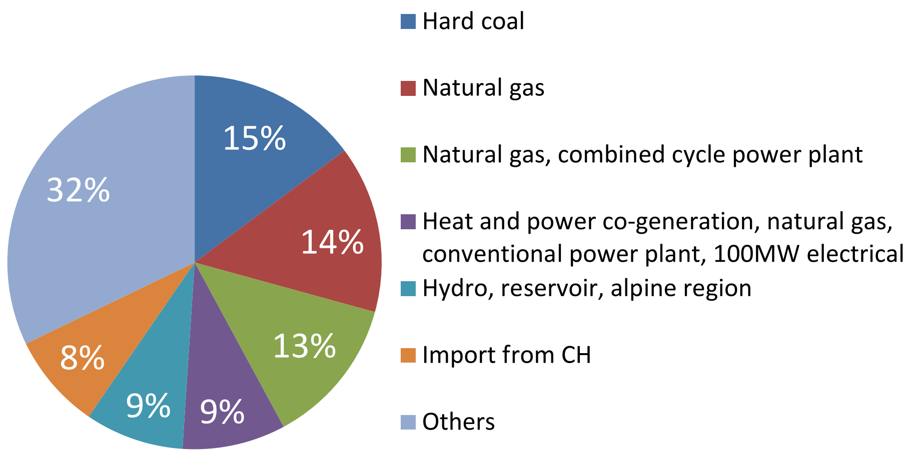

Figure 32: Electricity Italian country mix

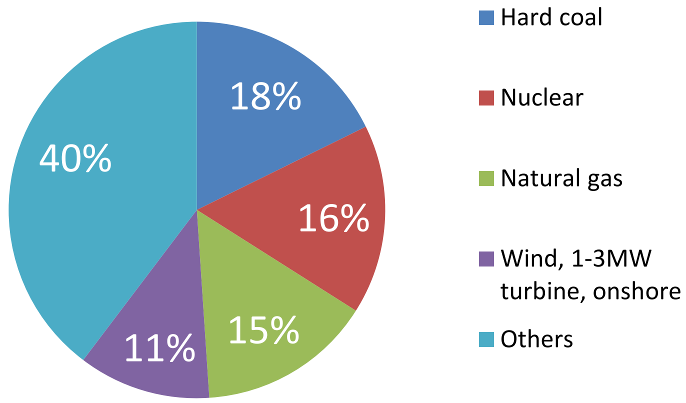

Figure 33: Electricity Spanish country mix

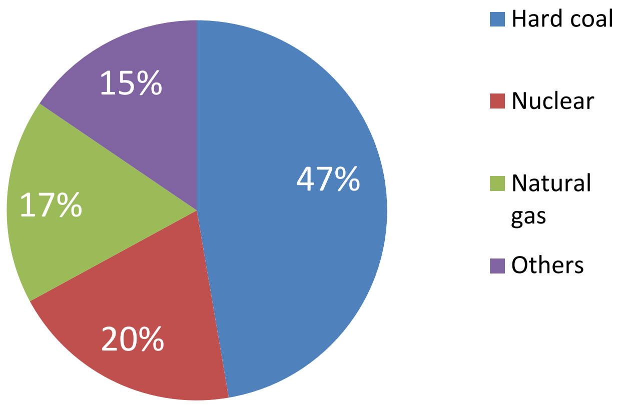

Figure 34: Electricity USA country mix

5.1.1 Changing the cements and keeping constant the plant

There are three different types of cements used in this simulation, CEM I, CEM II ALL and CEM IV A V. As it was previously said CEM I is the Portland cement, CEM II ALL is Portland cement with high value of limestone and CEM IV A V is Pozzolanic cement. Each of them produced in different plants all around Italy.

It is important to say that the three of them are produced with the same compression resistance, it means that their life phase is the same and this is why it is possible to compare them and their impacts.

ROBILANTE PLANT

Table 23: Absolute values environmental impacts comparison between cements in Robilante plant

		CEM I				CEM II ALL			
Impact category	Unit	MATERIALS	TRANSPORTS	LABORATORY	Total	MATERIALS	TRANSPORTS	LABORATORY	Total
Climate change	kg CO2 eq	6.28E-01	2.20E-02	1.04E-01	7.54E-01	6.22E-01	2.20E-02	1.04E-01	7.48E-01
Ozone depletion	kg CFC-11 eq	3.60E-03	4.04E-04	1.16E-03	5.17E-03	3.58E-03	4.04E-04	1.16E-03	5.14E-03
Terrestrial acidification	kg SO2 eq	2.41E-03	8.67E+00	4.00E-04	2.90E-03	2.42E-03	8.67E+00	4.00E-04	2.91E-03
Freshwater eutrophication	kg P eq	3.50E-04	1.81E-01	2.66E+00	3.78E-04	3.49E-04	1.81E-01	2.66E+00	3.77E-04
Marine eutrophication	kg N eq	9.66E+00	4.30E-01	1.40E+00	1.15E-04	9.66E+00	4.30E-01	1.40E+00	1.15E-04
Human toxicity	kg 1,4-DB eq	3.60E-01	8.70E-03	1.98E-02	3.88E-01	3.60E-01	8.70E-03	1.98E-02	3.88E-01
Photochemical oxidant formation	kg NMVOC	2.60E-03	1.18E-04	2.16E-04	2.93E-03	2.60E-03	1.18E-04	2.16E-04	2.93E-03
Particulate matter formation	kg PM10 eq	2.17E-03	5.01E+00	1.31E-04	2.35E-03	2.17E-03	5.01E+00	1.31E-04	2.35E-03
Terrestrial ecotoxicity	kg 1,4-DB eq	4.13E+00	1.62E+00	3.85E-01	6.13E+00	4.13E+00	1.62E+00	3.85E-01	6.13E+00
Freshwater ecotoxicity	kg 1,4-DB eq	1.15E-02	1.72E-04	1.13E-03	1.28E-02	1.15E-02	1.72E-04	1.13E-03	1.28E-02
Marine ecotoxicity	kg 1,4-DB eq	1.12E-02	2.61E-04	1.01E-03	1.25E-02	1.12E-02	2.61E-04	1.01E-03	1.25E-02
Ionising radiation	kBq U235 eq	2.42E-02	1.68E-03	1.51E-02	4.10E-02	2.42E-02	1.68E-03	1.51E-02	4.10E-02
Agricultural land occupation	m2a	1.08E-02	2.95E-04	3.86E-03	1.50E-02	1.08E-02	2.95E-04	3.86E-03	1.50E-02
Urban land occupation	m2a	6.84E-03	1.18E-03	4.44E-04	8.47E-03	6.84E-03	1.18E-03	4.44E-04	8.47E-03
Natural land transformation	m2	6.61E+00	8.63E-01	1.38E+00	8.86E+00	6.61E+00	8.63E-01	1.38E+00	8.86E+00
Water depletion	m3	1.18E-02	7.23E+00	1.43E-03	1.33E-02	1.18E-02	7.23E+00	1.43E-03	1.33E-02
Metal depletion	kg Fe eq	4.92E-01	7.95E-04	1.37E-03	4.94E-01	4.92E-01	7.95E-04	1.37E-03	4.95E-01
Fossil depletion	kg oil eq	1.34E-01	7.96E-03	2.94E-02	1.71E-01	1.34E-01	7.96E-03	2.94E-02	1.71E-01

Although the data can be compared from the Table 23, several charts have been done to better show the results.

In the following Table 24, a comparison between the total impacts is carried out: in particular it is shown which cement impacts are higher in each category by the reduction coefficient calculated dividing the total impacts of the cement by the maximum of the total impacts between the two cements.

Table 24: Reduction coefficients of total impacts between CEM I and CEM II ALL in Robilante plant

Impact category	CEM I	CEM II ALL
Climate change	100	99,26
Ozone depletion	100	99,55
Terrestrial acidification	99,73	100
Freshwater eutrophication	100	99,72
Marine eutrophication	99,99	100
Human toxicity	99,99	100
Photochemical oxidant formation	99,99	100
Particulate matter formation	99,93	100
Terrestrial ecotoxicity	99,99	100
Freshwater ecotoxicity	99,99	100
Marine ecotoxicity	99,99	100
Ionising radiation	99,98	100
Agricultural land occupation	99,99	100
Urban land occupation	99,99	100
Natural land transformation	99,99	100
Water depletion	99,99	100
Metal depletion	99,82	100
Fossil depletion	100	99,91

As it can be seen from the Table 24 and the Figure 35, CEM I is more impacting than CEM II ALL in climate change, ozone depletion, freshwater eutrophication and fossil depletion being CEM II ALL more impacting in all the rest of categories.

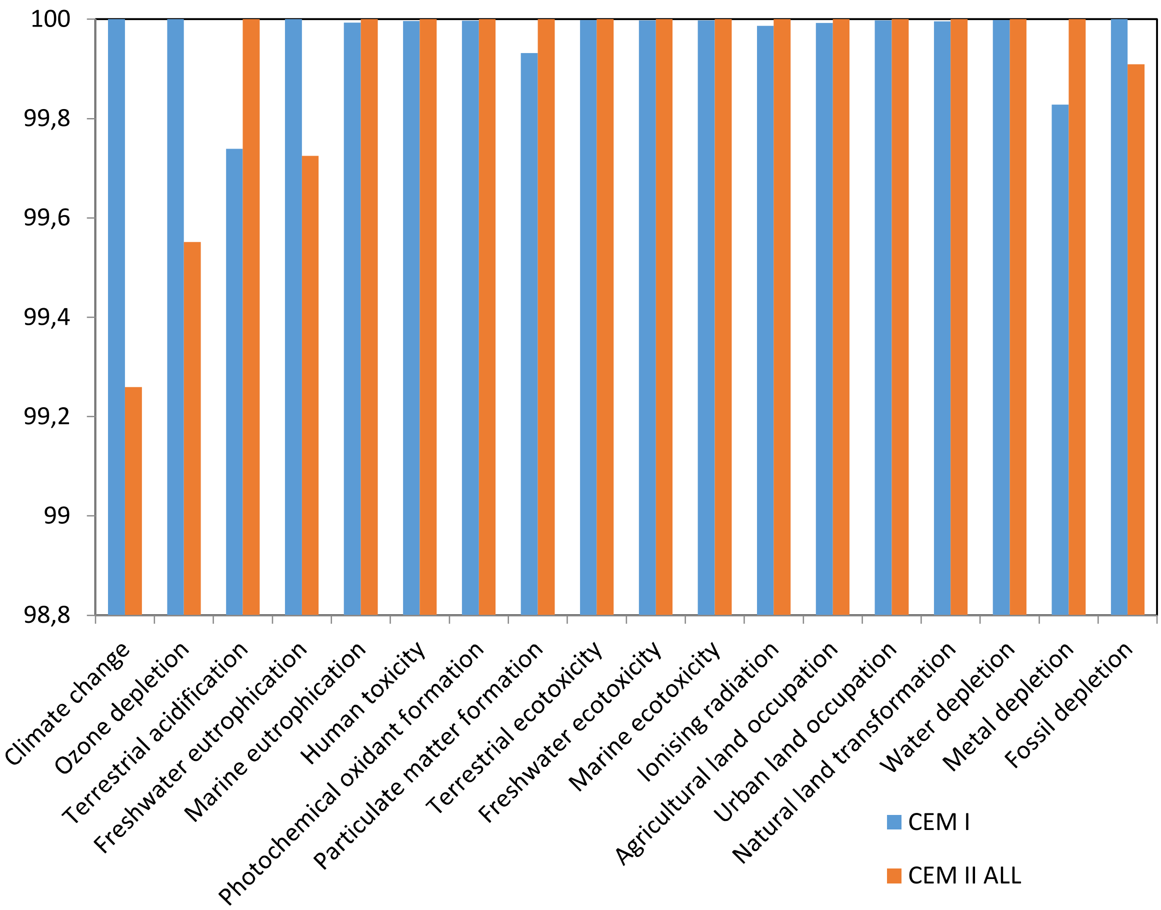

Figure 35: Reduction values of total impacts for Robilante plant

As the materials phase is the one that impacts the most and the only one that varies (since only the cement is varying in this part of the study) the focus will be on it in the same way it was done for the total impacts:

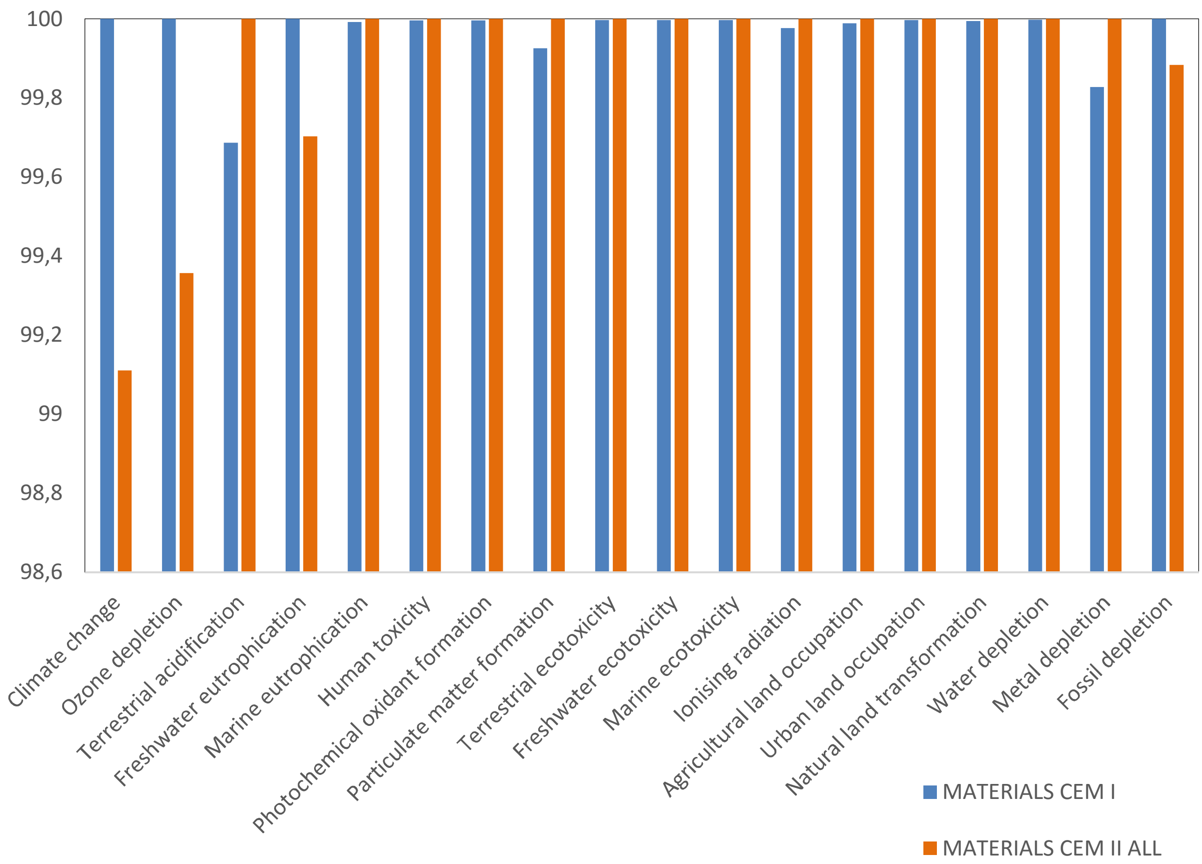

Figure 36: Reduction values of material impacts for Robilante plant

From Figure 36 can be confirmed that the most significant differences between the impacts of CEM I and CEM II ALL are climate change and ozone depletion.

TRINO PLANT

Table 25: Absolute values environmental impacts comparison between cements in Trino plant

		CEM II ALL				CEM IV A V			
Impact category	Unit	MATERIALS	TRANSPORT	LABORATORY	Total	MATERIALS	TRANSPORTS	LABORATORY	Total
Climate change	kg CO2 eq	6.21E-01	2.01E-02	1.04E-01	7.45E-01	6.17E-01	2.01E-02	1.04E-01	7.41E-01
Ozone depletion	kg CFC-11 eq	3.60E-03	3.69E-04	1.16E-03	5.14E-03	3.59E-03	3.69E-04	1.16E-03	5.12E-03
Terrestrial acidification	kg SO2 eq	2.38E-03	7.91E+00	4.00E-04	2.86E-03	2.35E-03	7.91E+00	4.00E-04	2.83E-03
Freshwater eutrophication	kg P eq	3.51E-04	1.66E-01	2.66E+00	3.79E-04	3.50E-04	1.66E-01	2.66E+00	3.78E-04
Marine eutrophication	kg N eq	9.66E+00	3.93E-01	1.40E+00	1.15E-04	9.66E+00	3.93E-01	1.40E+00	1.15E-04
Human toxicity	kg 1,4-DB eq	3.60E-01	7.95E-03	1.98E-02	3.87E-01	3.60E-01	7.95E-03	1.98E-02	3.87E-01
Photochemical oxidant formation	kg NMVOC	2.60E-03	1.07E-04	2.16E-04	2.92E-03	2.60E-03	1.07E-04	2.16E-04	2.92E-03
Particulate matter formation	kg PM10 eq	2.16E-03	4.58E+00	1.31E-04	2.34E-03	2.16E-03	4.58E+00	1.31E-04	2.33E-03
Terrestrial ecotoxicity	kg 1,4-DB eq	4.13E+00	1.48E+00	3.85E-01	5.99E+00	4.13E+00	1.48E+00	3.85E-01	5.99E+00
Freshwater ecotoxicity	kg 1,4-DB eq	1.15E-02	1.57E-04	1.13E-03	1.28E-02	1.15E-02	1.57E-04	1.13E-03	1.28E-02
Marine ecotoxicity	kg 1,4-DB eq	1.12E-02	2.38E-04	1.01E-03	1.25E-02	1.12E-02	2.38E-04	1.01E-03	1.25E-02
Ionising radiation	kBq U235 eq	2.42E-02	1.53E-03	1.51E-02	4.09E-02	2.42E-02	1.53E-03	1.51E-02	4.08E-02
Agricultural land occupation	m2a	1.08E-02	2.69E-04	3.86E-03	1.49E-02	1.08E-02	2.69E-04	3.86E-03	1.49E-02
Urban land occupation	m2a	6.84E-03	1.08E-03	4.44E-04	8.36E-03	6.84E-03	1.08E-03	4.44E-04	8.36E-03
Natural land transformation	m2	6.61E+00	7.88E-01	1.38E+00	8.79E+00	6.61E+00	7.88E-01	1.38E+00	8.79E+00
Water depletion	m3	1.18E-02	6.60E+00	1.43E-03	1.33E-02	1.18E-02	6.60E+00	1.43E-03	1.33E-02
Metal depletion	kg Fe eq	4.92E-01	7.26E-04	1.37E-03	4.95E-01	4.92E-01	7.26E-04	1.37E-03	4.94E-01
Fossil depletion	kg oil eq	1.34E-01	7.27E-03	2.94E-02	1.70E-01	1.33E-01	7.27E-03	2.94E-02	1.70E-01

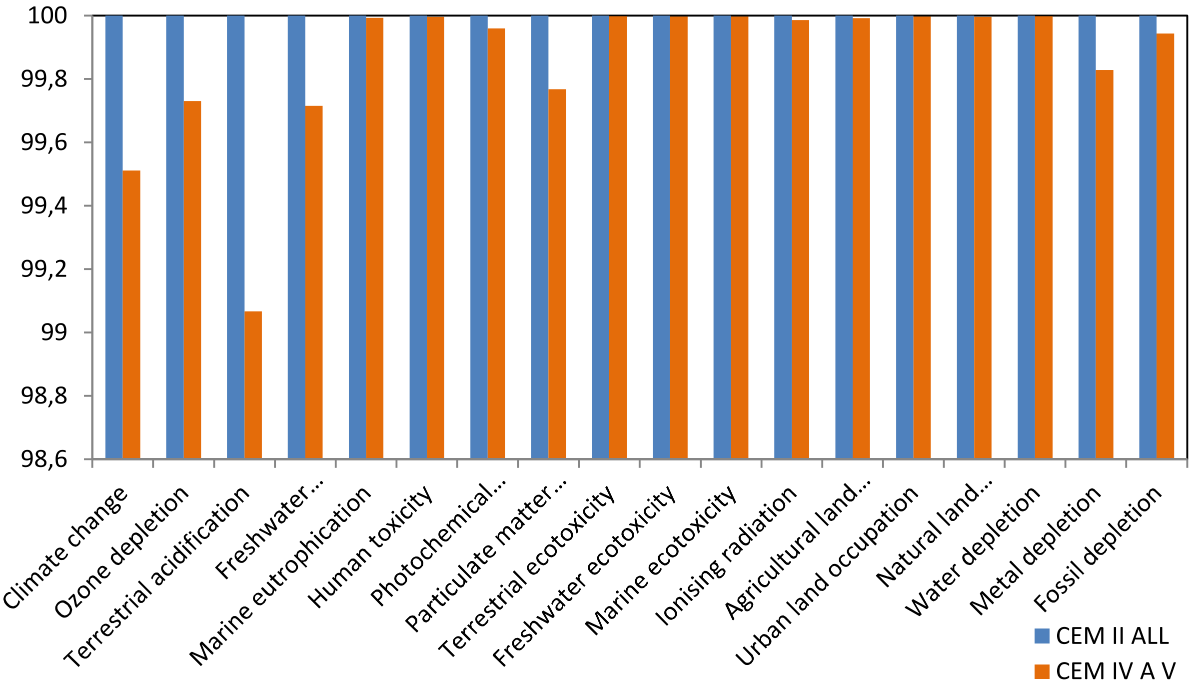

Figure 37: Reduction values of total impacts for Trino plant

In Figure 37 and Figure 38 it can be seen that CEM II ALL has more environmental impacts than CEM IV A V in all categories, especially in terrestrial acidification (100% for CEM II ALL versus 99 % for CEM IV A V for material impacts).

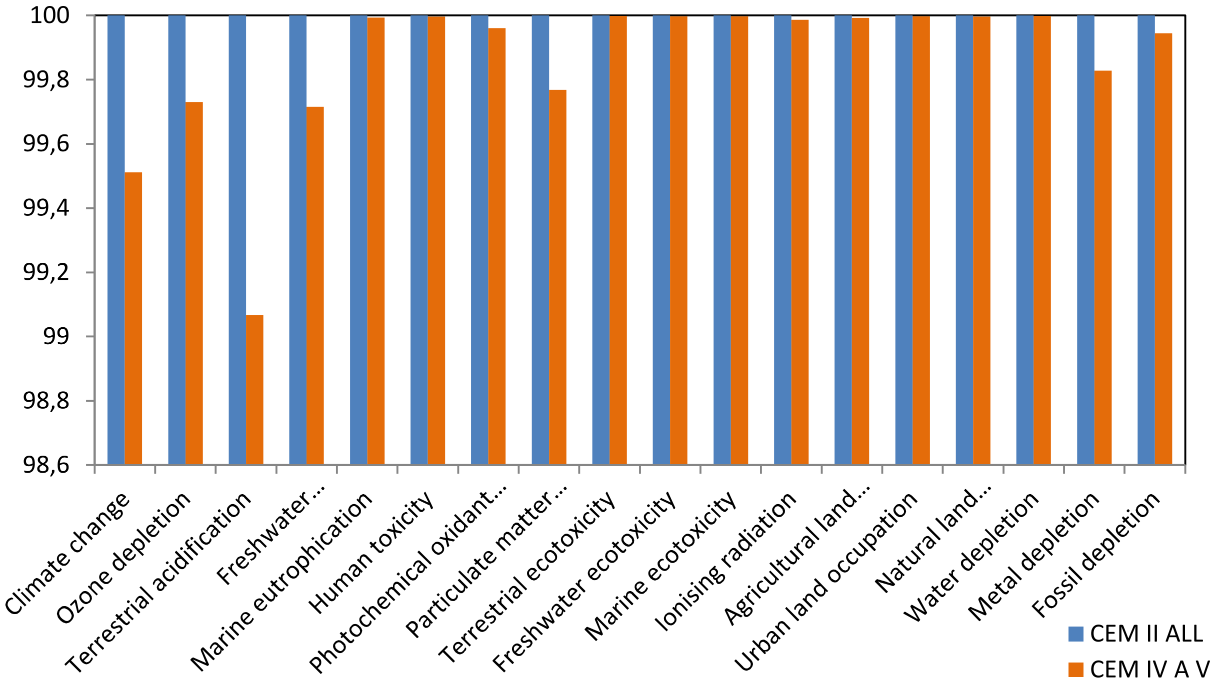

Figure 38: Reduction values of material impacts for Trino plant

VERNASCA PLANT

Table 26: Absolute values environmental impacts comparison between cements in Vernasca plant

		CEM II ALL				CEM IV A V			
Impact category	Unit	MATERIALS	TRANSPORT	LABORATORY	Total	MATERIALS	TRANSPORTS	LABORATORY	Total
Climate change	kg CO2 eq	6.22E-01	1.98E-02	1.04E-01	7.46E-01	6.14E-01	1.98E-02	1.04E-01	7.37E-01
Ozone depletion	kg CFC-11 eq	3.69E-03	3.64E-04	1.16E-03	5.22E-03	3.65E-03	3.64E-04	1.16E-03	5.17E-03
Terrestrial acidification	kg SO2 eq	2.44E-03	7.81E+00	4.00E-04	2.92E-03	2.36E-03	7.81E+00	4.00E-04	2.84E-03
Freshwater eutrophication	kg P eq	3.52E-04	1.64E-01	2.66E+00	3.80E-04	3.48E-04	1.64E-01	2.66E+00	3.76E-04
Marine eutrophication	kg N eq	9.66E+00	3.88E-01	1.40E+00	1.14E-04	9.66E+00	3.88E-01	1.40E+00	1.14E-04
Human toxicity	kg 1,4-DB eq	3.60E-01	7.84E-03	1.98E-02	3.87E-01	3.60E-01	7.84E-03	1.98E-02	3.87E-01
Photochemical oxidant formation	kg NMVOC	2.60E-03	1.06E-04	2.16E-04	2.93E-03	2.60E-03	1.06E-04	2.16E-04	2.92E-03
Particulate matter formation	kg PM10 eq	2.17E-03	4.52E+00	1.31E-04	2.35E-03	2.16E-03	4.52E+00	1.31E-04	2.33E-03
Terrestrial ecotoxicity	kg 1,4-DB eq	4.13E+00	1.46E+00	3.85E-01	5.97E+00	4.13E+00	1.46E+00	3.85E-01	5.97E-01
Freshwater ecotoxicity	kg 1,4-DB eq	1.15E-02	1.55E-04	1.13E-03	1.28E-02	1.15E-02	1.55E-04	1.13E-03	1.28E-02
Marine ecotoxicity	kg 1,4-DB eq	1.12E-02	2.35E-04	1.01E-03	1.25E-02	1.12E-02	2.35E-04	1.01E-03	1.25E-02
Ionising radiation	kBq U235 eq	2.42E-02	1.51E-03	1.51E-02	4.08E-02	2.42E-02	1.51E-03	1.51E-02	4.08E-02
Agricultural land occupation	m2a	1.08E-02	2.66E-04	3.86E-03	1.49E-02	1.08E-02	2.66E-04	3.86E-03	1.49E-02
Urban land occupation	m2a	6.84E-03	1.07E-03	4.44E-04	8.35E-03	6.84E-03	1.07E-03	4.44E-04	8.35E-03
Natural land transformation	m2	6.61E+00	7.78E-03	1.38E+00	8.78E-01	6.61E+00	7.78E-03	1.38E+00	8.78E+00
Water depletion	m3	1.18E-02	6.51E+00	1.43E-03	1.33E-02	1.18E-02	6.51E+00	1.43E-03	1.33E-02
Metal depletion	kg Fe eq	4.92E-01	7.16E-04	1.37E-03	4.95E-01	4.92E-01	7.16E-04	1.37E-03	4.94E-01
Fossil depletion	kg oil eq	1.32E-01	7.17E-03	2.94E-02	1.68E-01	1.32E-01	7.17E-03	2.94E-02	1.68E-01

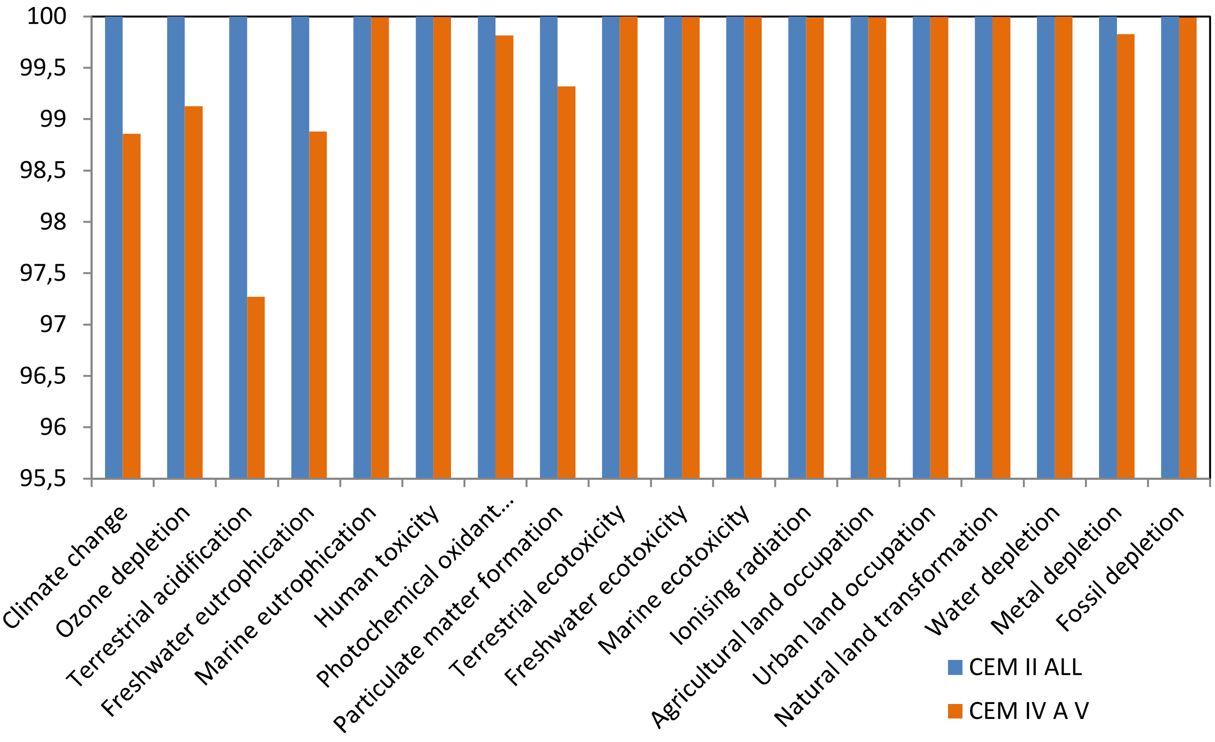

Figure 39: Reduction values of total impacts for Vernasca plant

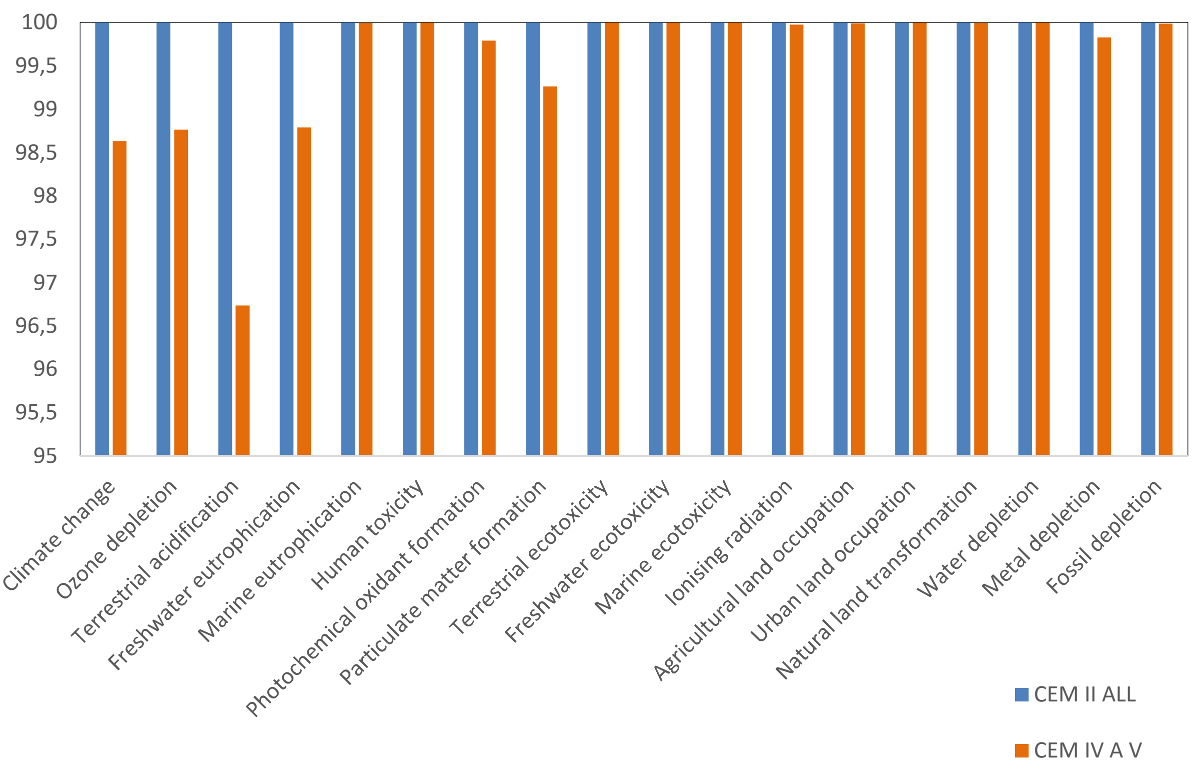

Figure 40: Reduction values of material impacts for Trino plant

In this case CEM II ALL has more impacts in all categories than CEM IV A V (See Figure 39 and Figure 40) being the most significant difference terrestrial acidification (100 % for CEM II versus 96.5% for CEM IV A V for material impacts).

GUIDONIA PLANT

Table 27: Absolute values environmental impacts comparison between cements in Guidonia plant

		CEM II ALL				CEM IV A V			
Impact category	Unit	MATERIALS	TRANSPORTS	LABORATORY	Total	MATERIALS	TRANSPORTS	LABORATORY	Total
Climate change	kg CO2 eq	6.28E-01	2.84E-02	1.04E-01	7.60E-01	6.18E-01	2.84E-02	1.04E-01	7.50E-01
Ozone depletion	kg CFC-11 eq	3.77E-03	5.23E-04	1.16E-03	5.45E-04	3.70E-03	5.23E-04	1.16E-03	5.39E-03
Terrestrial acidification	kg SO2 eq	2.48E-03	1.12E-04	4.00E-04	2.99E-03	2.38E-03	1.12E-04	4.00E-04	2.89E-03
Freshwater eutrophication	kg P eq	3.53E-04	2.35E-01	2.66E+00	3.82E-04	3.49E-04	2.35E-01	2.66E+00	3.78E-04
Marine eutrophication	kg N eq	9.66E+00	5.57E-01	1.40E+00	1.16E-04	9.66E+00	5.57E-01	1.40E+00	1.16E-04
Human toxicity	kg 1,4-DB eq	3.60E-01	1.13E-02	1.98E-02	3.91E-01	3.60E-01	1.13E-02	1.98E-02	3.91E-01
Photochemical oxidant formation	kg NMVOC	2.60E-03	1.52E-04	2.16E-04	2.97E-03	2.60E-03	1.52E-04	2.16E-04	2.97E-03
Particulate matter formation	kg PM10 eq	2.18E-03	6.49E+00	1.31E-04	2.38E-03	2.16E-03	6.49E+00	1.31E-04	2.36E-03
Terrestrial ecotoxicity	kg 1,4-DB eq	4.13E+00	2.09E+00	3.85E-01	6.60E-02	4.13E+00	2.09E+00	3.85E-01	6.60E+00
Freshwater ecotoxicity	kg 1,4-DB eq	1.15E-02	2.22E-04	1.13E-03	1.29E-02	1.15E-02	2.22E-04	1.13E-03	1.29E-02
Marine ecotoxicity	kg 1,4-DB eq	1.12E-02	3.38E-04	1.01E-03	1.26E-02	1.12E-02	3.38E-04	1.01E-03	1.26E-02
Ionising radiation	kBq U235 eq	2.42E-02	2.17E-03	1.51E-02	4.15E-02	2.42E-02	2.17E-03	1.51E-02	4.15E-02
Agricultural land occupation	m2a	1.08E-02	3.82E-04	3.86E-03	1.51E-02	1.08E-02	3.82E-04	3.86E-03	1.51E-02
Urban land occupation	m2a	6.84E-03	1.53E-03	4.44E-04	8.81E-03	6.84E-03	1.53E-03	4.44E-04	8.81E-03
Natural land transformation	m2	6.61E+00	1.12E+00	1.38E+00	9.12E+00	6.61E+00	1.12E+00	1.38E+00	9.11E+00
Water depletion	m3	1.18E-02	9.35E-01	1.43E-03	1.34E-02	1.18E-02	9.35E-01	1.43E-03	1.34E-02
Metal depletion	kg Fe eq	4.92E-01	1.03E-03	1.37E-03	4.95E-01	4.92E-01	1.03E-03	1.37E-03	4.94E-01
Fossil depletion	kg oil eq	1.32E-01	1.03E-02	2.94E-02	1.71E-01	1.32E-01	1.03E-02	2.94E-02	1.71E-01

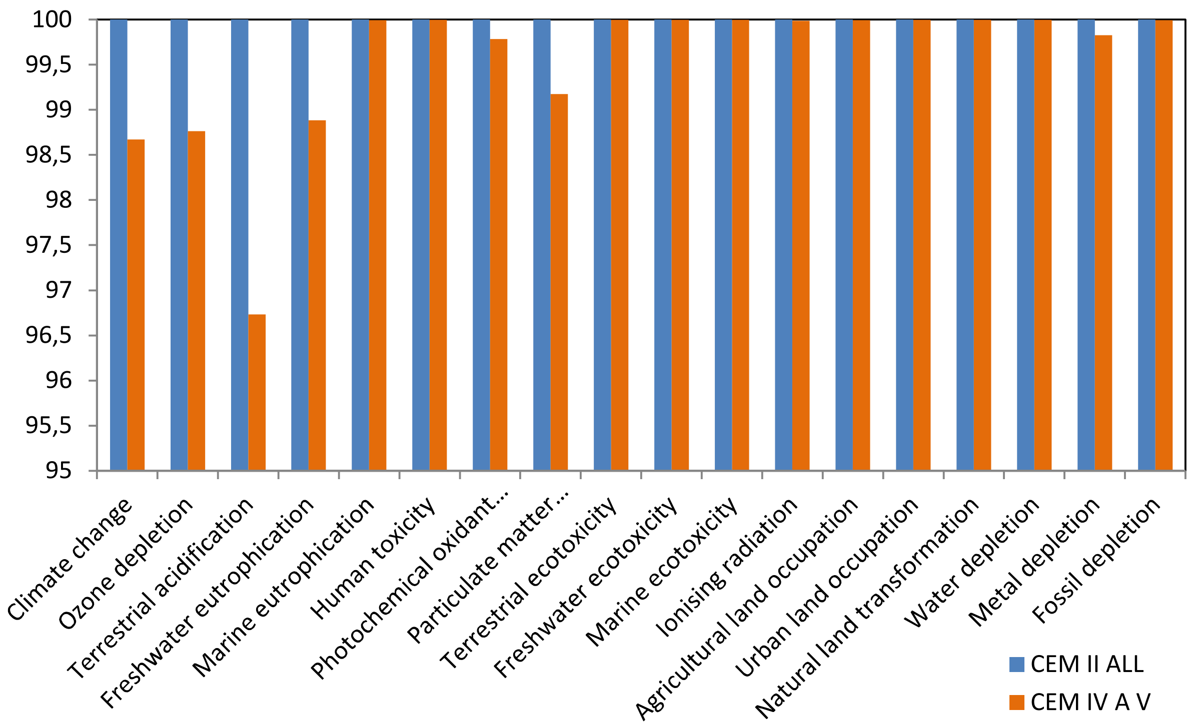

Figure 41: Reduction values of total impacts for Guidonia plant

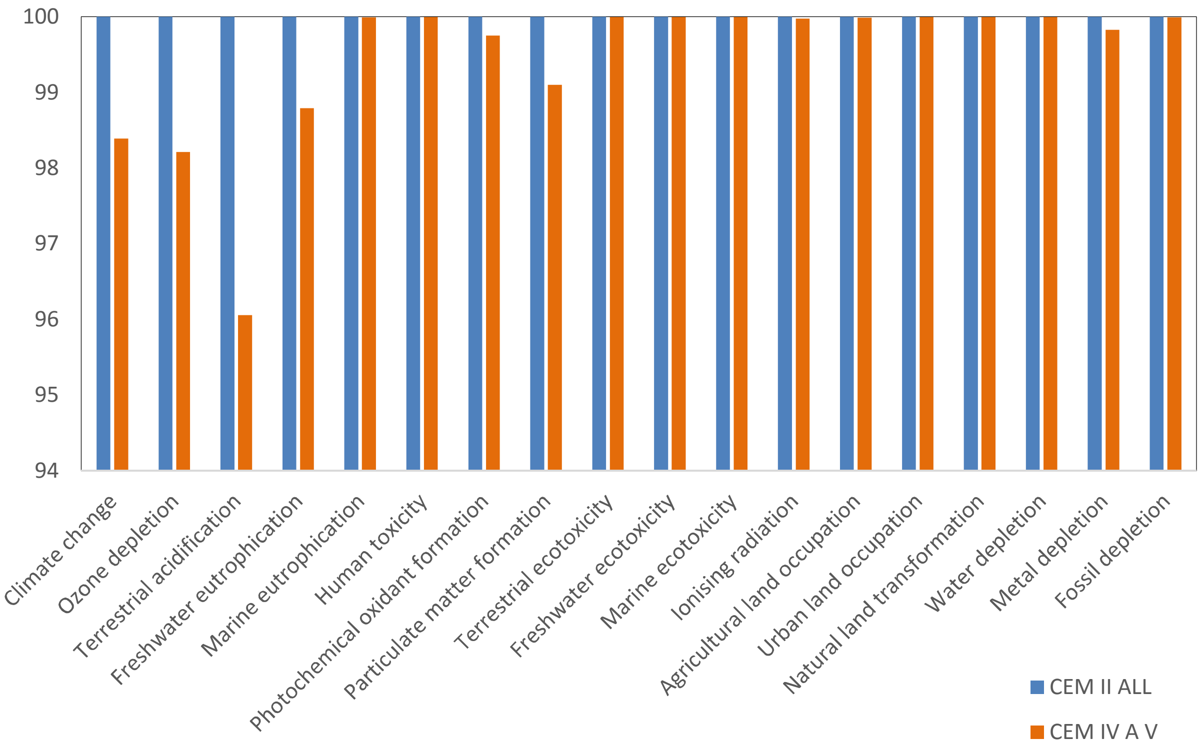

Figure 42: Reduction values of material impacts for Guidonia plant

All coincides with the previous cases (See Figure 41 and Figure 42) being CEM II ALL more impacting than CEM IV A V and especially for terrestrial acidification (100% for CEM II ALL versus 96 % for CEM IV A V for material impacts).

AUGUSTA PLANT

Table 28: Absolute values environmental impacts comparison between cements in Augusta plant

		CEM I				CEM II ALL				CEM IV A V			
Impact category	Unit	MATERIALS	TRANSPORTS	LABORATORY	Total	MATERIALS	TRANSPORTS	LABORATORY	Total	MATERIALS	TRANSPORTS	LABORATORY	Total
Climate change	kg CO2 eq	6.31E-01	4.23E-02	1.04E-01	7.77E-01	6.22E-01	4.23E-02	1.04E-01	7.68E-01	6.18E-01	4.23E-02	1.04E-01	7.64E-01
Ozone depletion	kg CFC-11 eq	3.76E-08	7.80E-09	1.16E-08	5.70E-08	3.71E-08	7.80E-09	1.16E-08	5.65E-08	3.69E-08	7.80E-09	1.16E-08	5.63E-08
Terrestrial acidification	kg SO2 eq	2.38E-03	1.67E-04	4.00E-04	2.95E-03	2.38E-03	1.67E-04	4.00E-04	2.95E-03	2.19E-03	1.67E-04	4.00E-04	2.75E-03
Freshwater eutrophication	kg P eq	3.52E-04	3.50E-06	2.66E-05	3.82E-04	3.52E-04	3.50E-06	2.66E-05	3.82E-04	3.51E-04	3.50E-06	2.66E-05	3.81E-04
Marine eutrophication	kg N eq	9.66E-05	8.29E-06	1.40E-05	1.19E-04	9.66E-05	8.29E-06	1.40E-05	1.19E-04	9.66E-05	8.29E-06	1.40E-05	1.19E-04
Human toxicity	kg 1,4-DB eq	3.60E-01	1.68E-02	1.98E-02	3.96E-01	3.60E-01	1.68E-02	1.98E-02	3.96E-01	3.60E-01	1.68E-02	1.98E-02	3.96E-01
Photochemical oxidant formation	kg NMVOC	2.60E-03	2.27E-04	2.16E-04	3.04E-03	2.60E-03	2.27E-04	2.16E-04	3.04E-03	2.58E-03	2.27E-04	2.16E-04	3.03E-03
Particulate matter formation	kg PM10 eq	2.16E-03	9.66E-05	1.31E-04	2.39E-03	2.16E-03	9.66E-05	1.31E-04	2.39E-03	2.12E-03	9.66E-05	1.31E-04	2.35E-03
Terrestrial ecotoxicity	kg 1,4-DB eq	4.13E-05	3.11E-05	3.85E-06	7.63E-05	4.13E-05	3.11E-05	3.85E-06	7.63E-05	4.13E-05	3.11E-05	3.85E-06	7.63E-05
Freshwater ecotoxicity	kg 1,4-DB eq	1.15E-02	3.31E-04	1.13E-03	1.30E-02	1.15E-02	3.31E-04	1.13E-03	1.30E-02	1.15E-02	3.31E-04	1.13E-03	1.30E-02
Marine ecotoxicity	kg 1,4-DB eq	1.12E-02	5.03E-04	1.01E-03	1.28E-02	1.12E-02	5.03E-04	1.01E-03	1.28E-02	1.12E-02	5.03E-04	1.01E-03	1.28E-02
Ionising radiation	kBq U235 eq	2.42E-02	3.24E-03	1.51E-02	4.25E-02	2.42E-02	3.24E-03	1.51E-02	4.26E-02	2.42E-02	3.24E-03	1.51E-02	4.25E-02
Agricultural land occupation	m2a	1.08E-02	5.68E-04	3.86E-03	1.52E-02	1.08E-02	5.68E-04	3.86E-03	1.52E-02	1.08E-02	5.68E-04	3.86E-03	1.52E-02
Urban land occupation	m2a	6.84E-03	2.28E-03	4.44E-04	9.56E-03	6.84E-03	2.28E-03	4.44E-04	9.56E-03	6.84E-03	2.28E-03	4.44E-04	9.56E-03
Natural land transformation	m2	6.61E-05	1.66E-05	1.38E-05	9.66E-05	6.61E-05	1.66E-05	1.38E-05	9.66E-05	6.61E-05	1.66E-05	1.38E-05	9.66E-05
Water depletion	m3	1.18E-02	1.39E-04	1.43E-03	1.34E-02	1.18E-02	1.39E-04	1.43E-03	1.34E-02	1.18E-02	1.39E-04	1.43E-03	1.34E-02
Metal depletion	kg Fe eq	4.92E-01	1.53E-03	1.37E-03	4.95E-01	4.92E-01	1.53E-03	1.37E-03	4.95E-01	4.92E-01	1.53E-03	1.37E-03	4.95E-01
Fossil depletion	kg oil eq	1.32E-01	1.53E-02	2.94E-02	1.76E-01	1.32E-01	1.53E-02	2.94E-02	1.76E-01	1.32E-01	1.53E-02	2.94E-02	1.76E-01

For Augusta plant it has been done simulations for the three cements since all the considered cements are produced in this plant. From the charts in Figure 43 and Figure 44 it is concluded that CEM IV A V has lower impact in all categories. Between CEM I and CEM II ALL there are differences, CEM II ALL reduces the impacts if compared with CEM I in climate change and ozone depletion (See Table 29).

Table 29: Reduction values of total impacts for Augusta plant

Impact category	CEM I	CEM II ALL	CEM IV A V
Climate change	100	98,83	98,32
Ozone depletion	100	99,06	98,70
Terrestrial acidification	99,99	100	93,48
Freshwater eutrophication	99,99	100	99,71
Marine eutrophication	99,99	100	99,99
Human toxicity	99,99	100	99,99
Photochemical oxidant formation	99,99	100	99,49
Particulate matter formation	99,99	100	98,38
Terrestrial ecotoxicity	99,99	100	99,99
Freshwater ecotoxicity	99,99	100	99,99
Marine ecotoxicity	99,99	100	99,99
Ionising radiation	99,98	100	99,98
Agricultural land occupation	99,99	100	99,99
Urban land occupation	99,99	100	99,99
Natural land transformation	99,99	100	99,99
Water depletion	99,99	100	99,99
Metal depletion	99,82	100	99,82
Fossil depletion	99,99	100	99,99

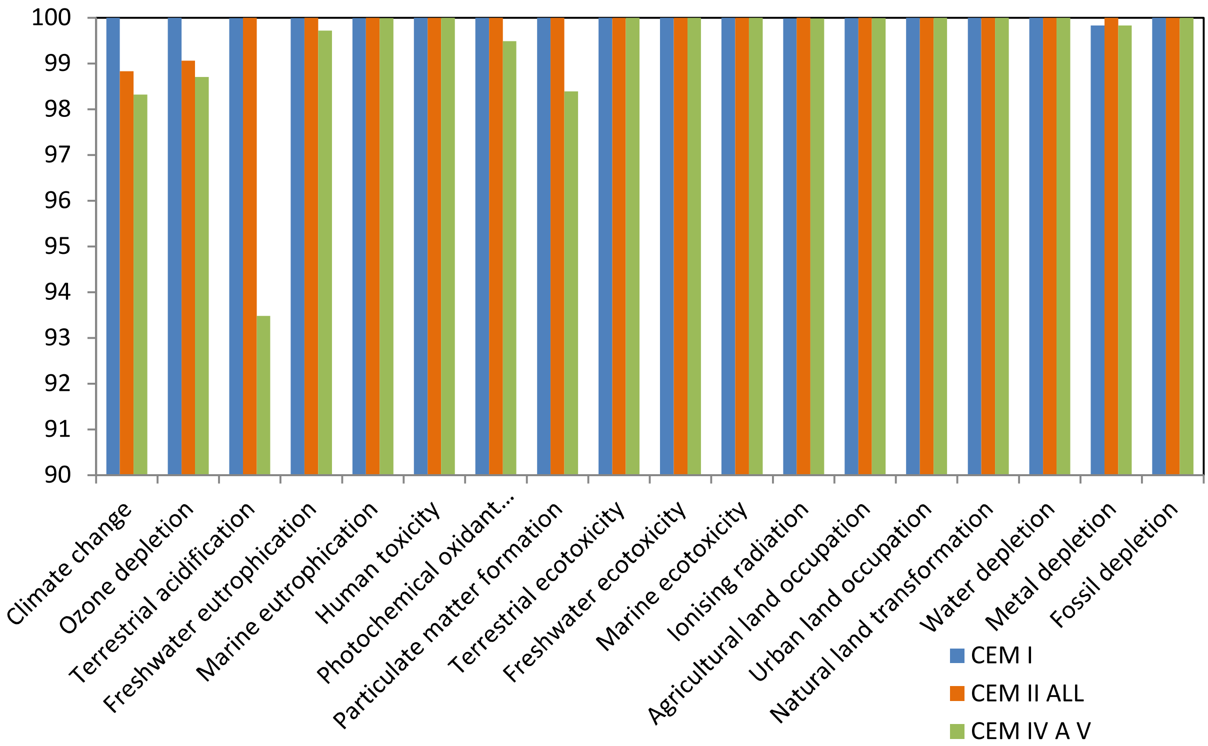

Figure 43: Reduction values of total impacts for Augusta plant

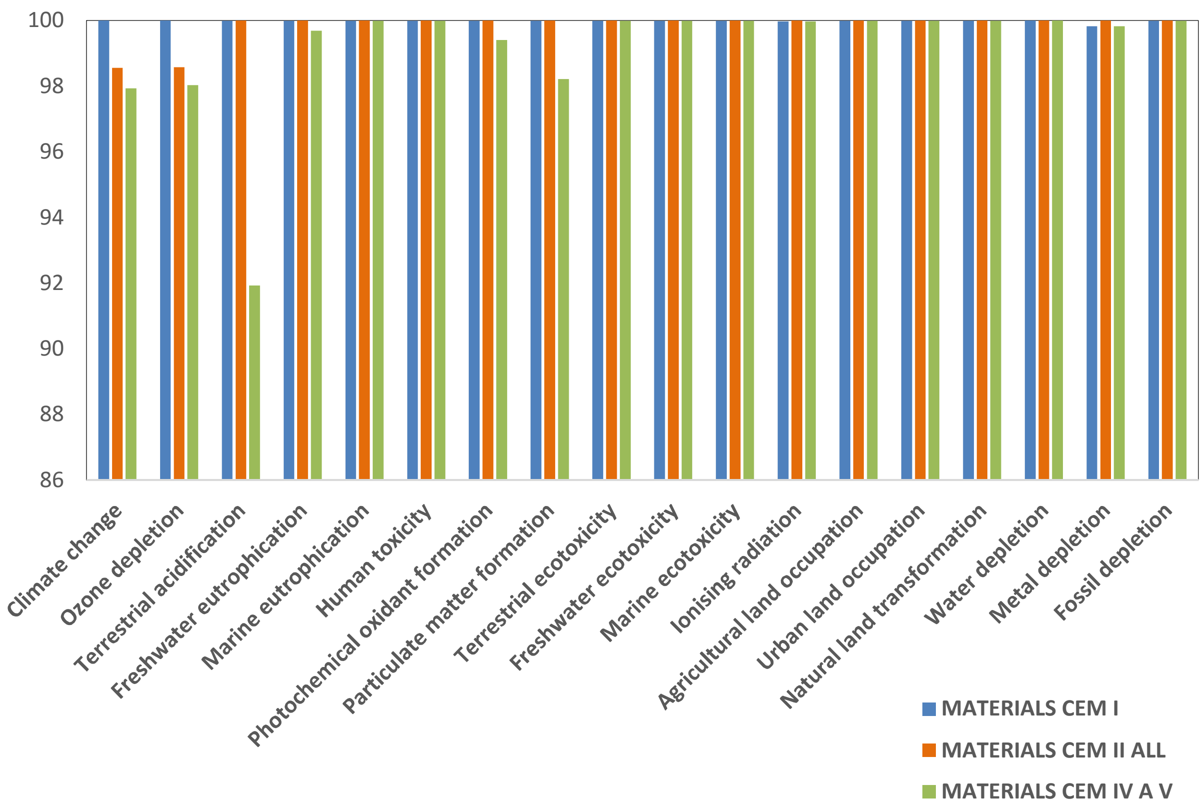

Figure 44: Reduction values of material impacts for Augusta plant

A common behavior of all the scenarios is that:

- Transport phase and laboratory phase are equal for all the cements in the same plant and this is not surprising since in this scenario the cements are changing but not the production plants and the manufacturing phase.
- CEM IV A V is the cement which has less impacts.
- CEM I is always more impacting in climate change and ozone depletion categories.

5.1.2 Changing the plant and keeping constant the cement

In this case significant changes will be seen in the transports phase as the plant and of course the kilometers to the Concrete Laboratory are changed.

CEM I

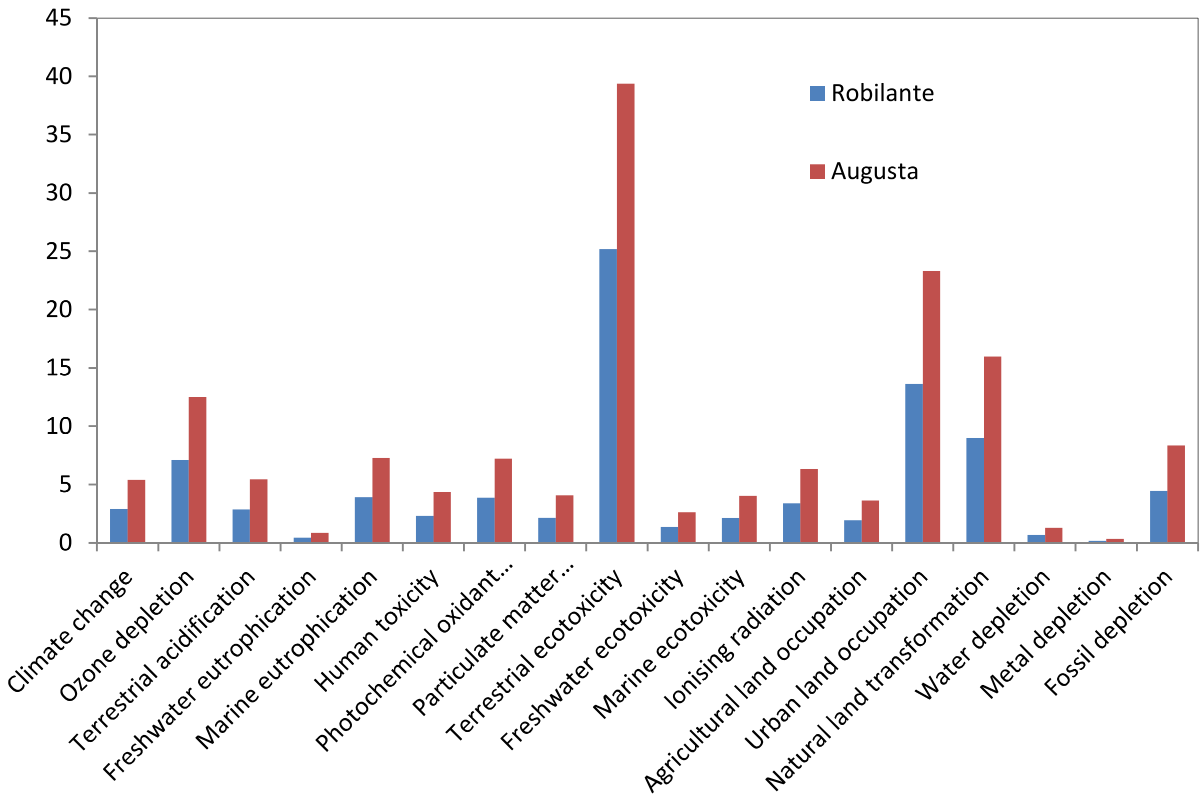

Figure 45: Percentage values transport impacts for CEM I

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CEM II ALL

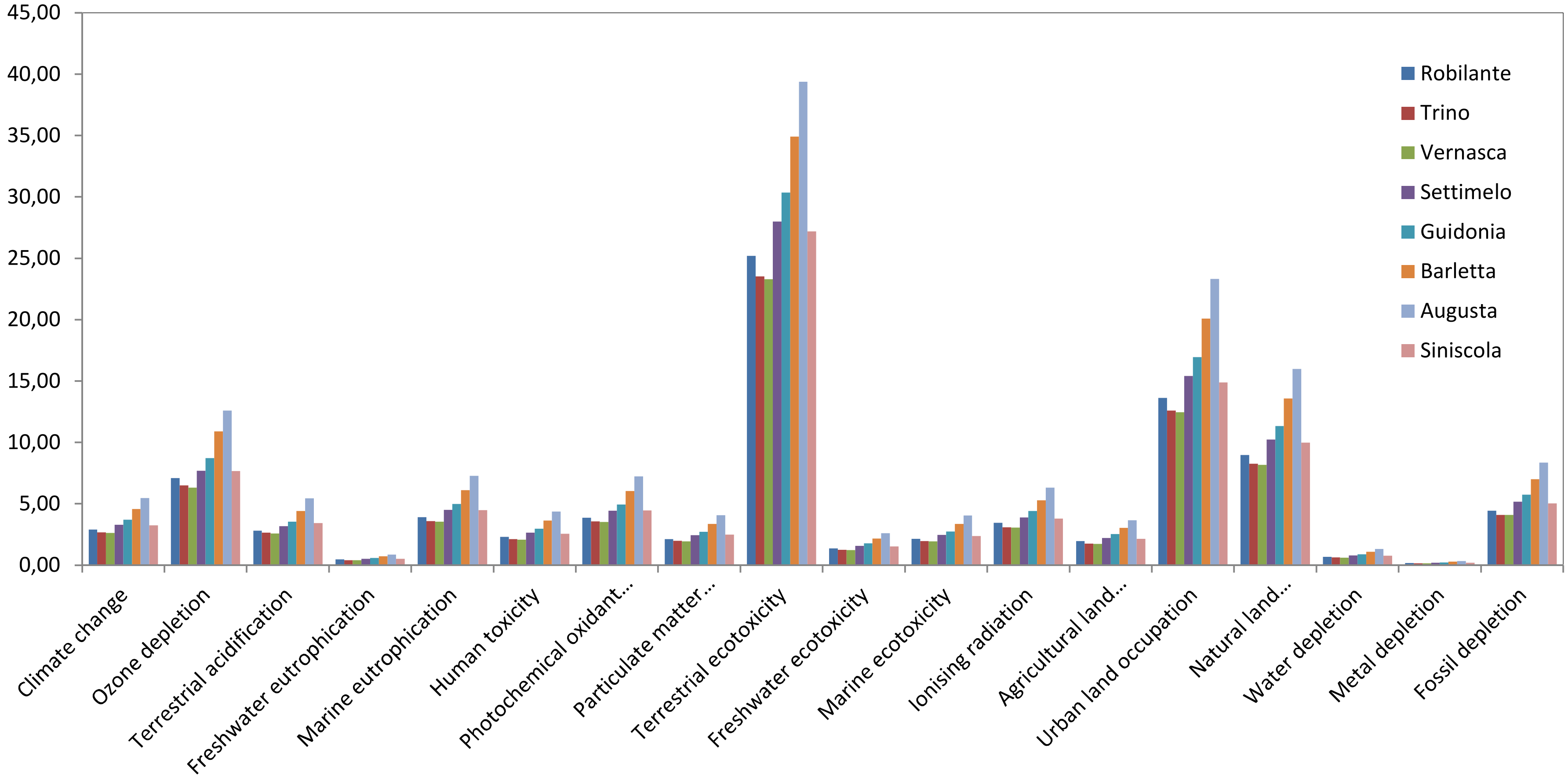

Figure 46: Percentage values transport impacts for CEM II ALL

CEM IV A V

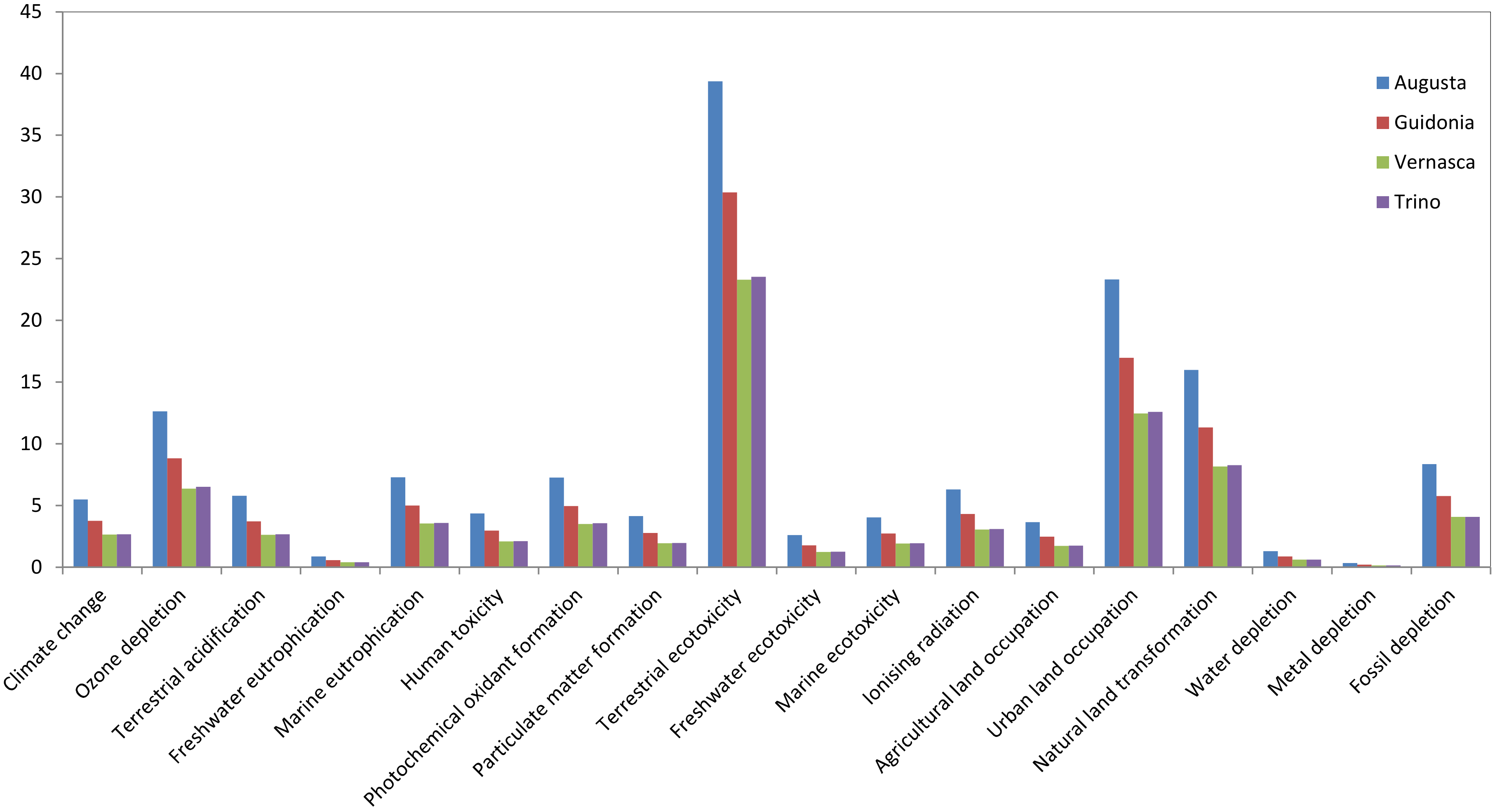

Figure 47: Percentage values transport impacts for CEM IV A V

From all previous figures (Figure 45, Figure 46 and Figure 47) it can be seen that Augusta is the plant which gives more transport impacts (near 40%). This is reasonable as it is the farthest one when travelling by road.

In the case of Augusta plant a normalization can be seen in Figure 48 in order to better understand the relative significance of impact category results. In the normalization stage, normalization references (NRs) are the characterized results of a reference system, typically a national or regional economy.

Doing it in SimaPro for all the scenarios it is found that Marine ecotoxicity and Freshwater ecotoxicity are the categories which impact more with a significant difference with respect to the others. On the other hand, the less impacting categories are ozone depletion and agricultural land operation.

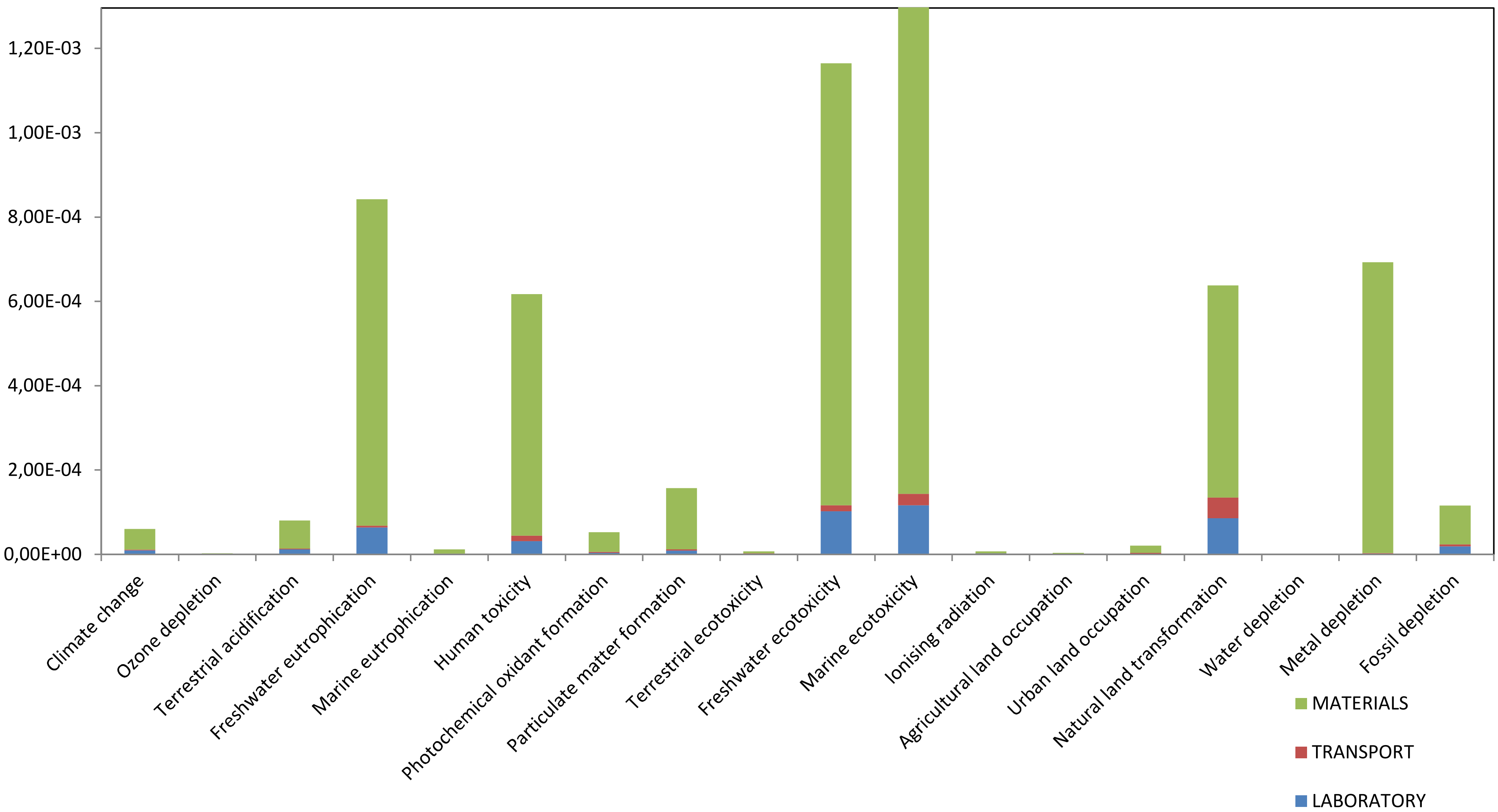

Figure 48: Normalization step done in SimaPro for CEM II ALL produced in Trino plant

Now, two charts will be done in order to see which plant reduces more the impacts in the most relevant categories.

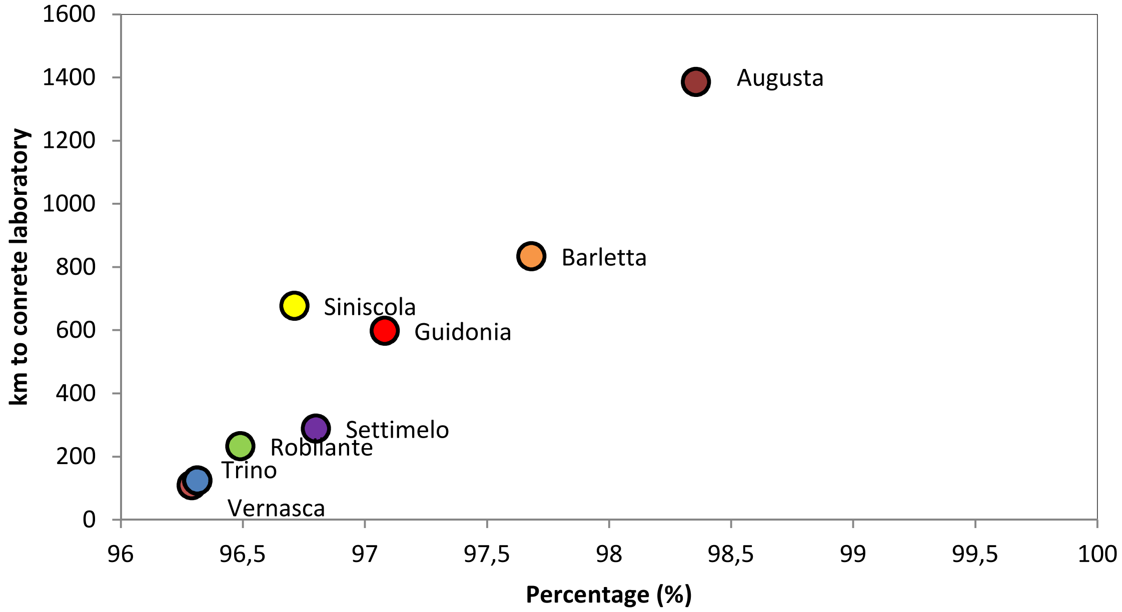

Figure 49: Percentage of global impacts versus kilometers to Concrete Laboratory for Marine ecotoxicity

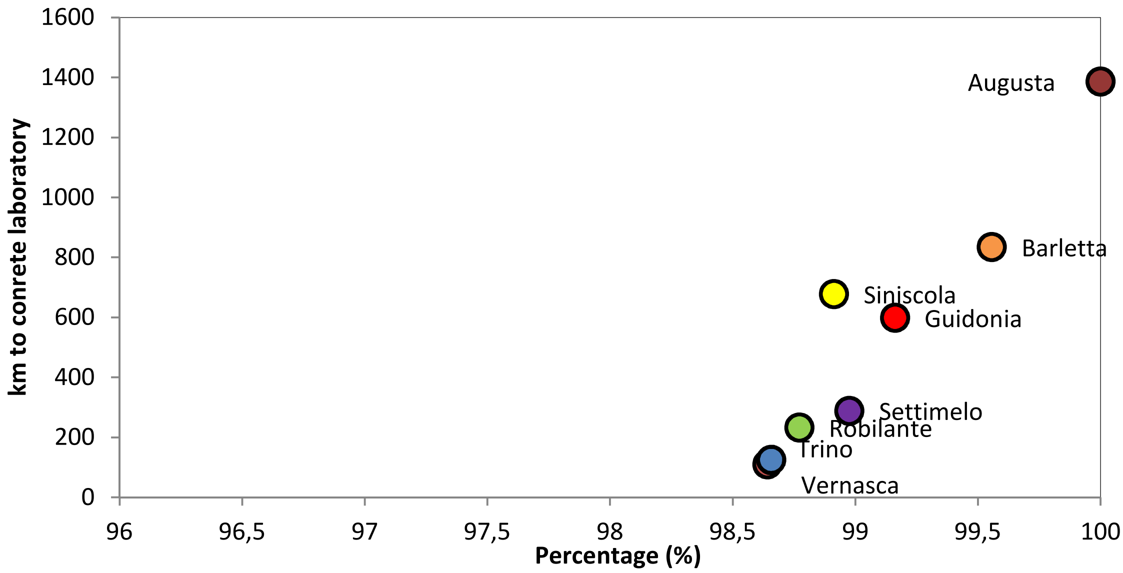

Figure 50: Percentage of global impacts versus kilometers to Concrete Laboratory for Freshwater ecotoxicity

From the previous charts (Figure 49 and Figure 50) some conclusions can be made:

- It is confirmed that Augusta plant is the most impacting one.
- The impacts increase with the distance to the concrete laboratory for all the scenarios except for Siniscola, this is because of the type of transport used to travel to the destination. As Siniscola is placed in an island a ferry is needed, and it seems that travelling by sea has less impacts than travelling by road.
- Trino and Vernasca are the less impacting plants.

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5.2 Life cycle analysis of a complex reinforced concrete structure

A complex reinforced concrete specimen has been considered to develop different scenarios changing the type of cement used and the distance of the cement supplier plant. Data that has been kept constant is summarized in the following Table 30:

Table 30: Constant data used for the simulation of a complex reinforced concrete structure

Variable	Value	Comments
Energy mix design consumption	0.15 kWh	Machines from Concrete Laboratory in Politenico di Milano
Energy installation consumption	0.055 kW	
Steel transport	199 km	Valbruna supplier
Aggregates transport	119 km	Torrazza
Cement amount	546.31 g	
Steel type and amount	1316.916 g	Reinforcing steel
Water type and amount	273.158 g	Deionized water
Aggregates type and amount	2327.30 g	Crushed limestone
Concrete cover thickness	55 mm	
Concrete height	60 mm	
Reinforcing steel diameter	20 mm	
Reinforcing steel height	100 mm	
Steel density	7850 kg/m^3	

IDEAL CASE

As in the case for a simple geometry the ideal case CEM I (Portland) in Robilante plant will be analysed in order to see which is the phase more impacting.

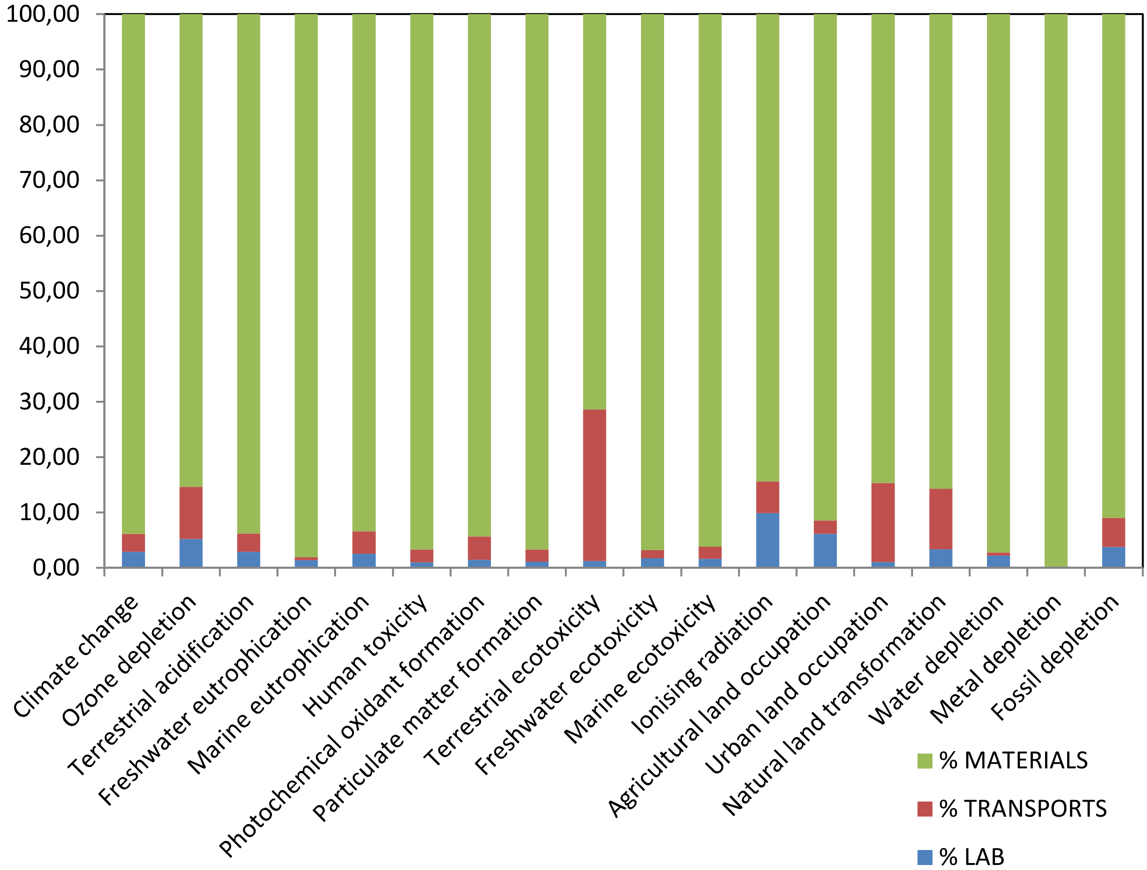

Figure 51: Environmental impacts using CEM I produced in Robilante plant

From Figure 51 and Table 31 it can be confirmed that the phase more impacting is materials phase as in the simple geometry.

Moreover, if Table 31 and Table 19 are compared it can be seen that for the complex geometry materials phase makes a significant increase, which seems logic as the amount of materials used is higher. Ranges for the simple geometry are 56-99% and for the complex geometry 71% to almost 100%.

Table 31: Percentage values of environmental impacts using CEM I produced in Robilante plant

	CEM I		
Impact category	% MATERIALS	% TRANSPORTS	% LAB
Climate change	93.84	3.23	2.93
Ozone depletion	85.39	9.43	5.18
Terrestrial acidification	93.78	3.30	2.92
Freshwater eutrophication	98.10	0.50	1.40
Marine eutrophication	93.39	4.07	2.54
Human toxicity	96.71	2.29	1.00
Photochemical oxidant formation	94.34	4.18	1.47
Particulate matter formation	96.71	2.19	1.10
Terrestrial ecotoxicity	71.40	27.35	1.25
Freshwater ecotoxicity	96.82	1.41	1.77
Marine ecotoxicity	96.20	2.19	1.62
Ionising radiation	84.37	5.73	9.90
Agricultural land occupation	91.45	2.44	6.11
Urban land occupation	84.65	14.32	1.03
Natural land transformation	85.70	10.94	3.36
Water depletion	97.22	0.58	2.19
Metal depletion	99.79	0.16	0.05
Fossil depletion	90.96	5.30	3.74

From Figure 51 and Table 31 it can be seen a significant reduction of laboratory phase (from 0.05 to almost 10%) with respect to the simple geometry (from 0.33 to 48 %) because of the increase of the cement amount. Again a comparison between Italian, Spanish and American electricity is done in Figure 52 confirming the results obtained for the simple geometry: US electricity is the most impacting one in almost all categories.

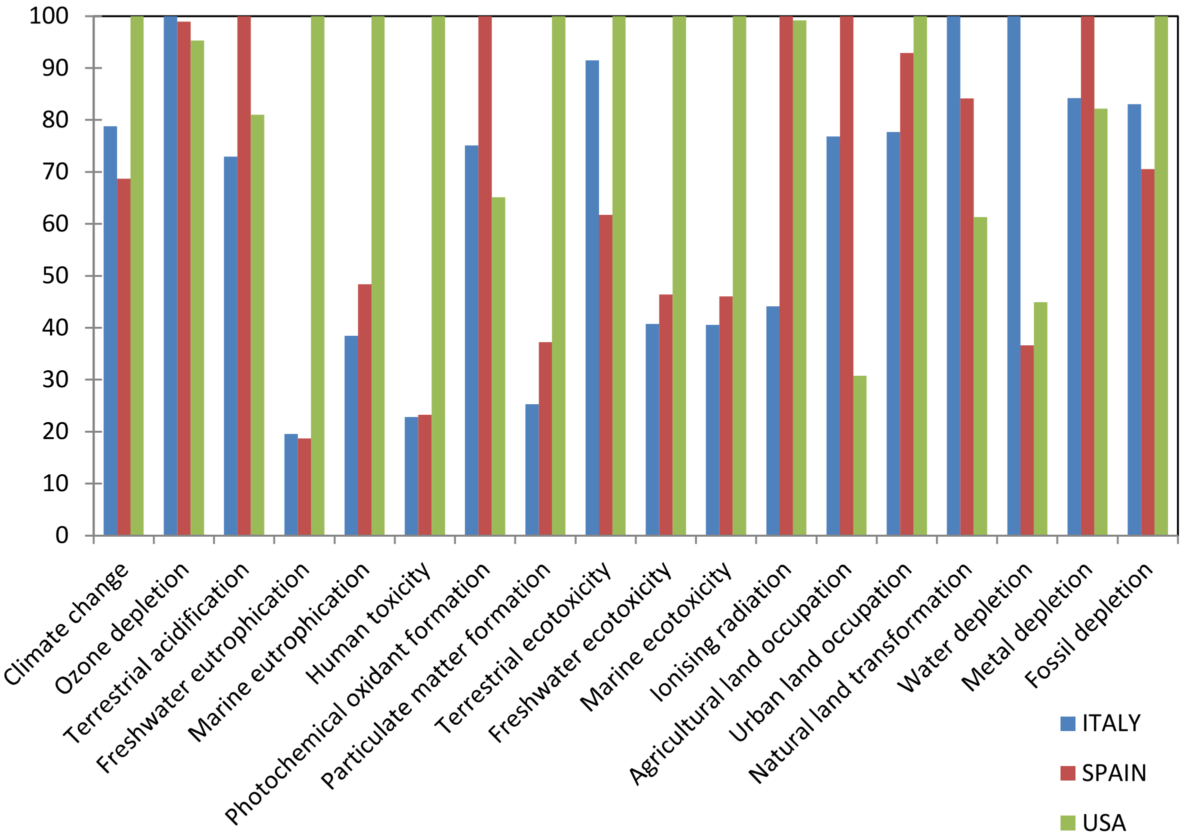

Figure 52: Reduction values comparison of laboratory impacts for CEM I produced in Robilante in Italy, Spain and United States for a complex geometry

Therefore, with these simulations changing the electricity it can be concluded that it depends on the country, being more impacting in the US. It also depends on the amount of materials, playing the laboratory phase an important role when few amounts are used. Finally, from (David J. M. Flower et al, 2007) can be concluded that the operational energy consumption can be considerably reduced when using Environmentally Sustainable Designs (ESD) on site when comparing with electricity used in laboratory scale.

5.2.1 Changing the cements and keeping constant the plant

The simulation has been done exactly following the same steps as in the case of a simple reinforced concrete structure.

ROBILANTE PLANT

Table 32: Absolute values environmental impacts comparison between cements in Robilante plant

		CEM I				CEM II ALL			
Impact category	Unit	MATERIALS	TRANSPORTS	LABORATORY	Total	MATERIALS	TRANSPORTS	LABORATORY	Total
Climate change	kg CO2 eq	3.33E+00	1.15E-01	1.04E-01	3.55E+00	3.31E+00	1.15E-01	1.04E-01	3.52E+00
Ozone depletion	kg CFC-11 eq	1.91E-07	2.10E-08	1.20E-08	2.24E-07	1.90E-07	2.10E-08	1.20E-08	2.23E-07
Terrestrial acidification	kg SO2 eq	1.28E-02	4.53E-04	4.00E-04	1.37E-02	1.29E-02	4.53E-04	4.00E-04	1.37E-02
Freshwater eutrophication	kg P eq	1.86E-03	9.48E-06	2.66E-05	1.90E-03	1.86E-03	9.48E-06	2.66E-05	1.89E-03
Marine eutrophication	kg N eq	5.16E-04	2.25E-05	1.40E-05	5.52E-04	5.16E-04	2.25E-05	1.40E-05	5.52E-04
Human toxicity	kg 1,4-DB eq	1.92E+00	4.54E-02	1.98E-02	1.99E+00	1.92E+00	4.54E-02	1.98E-02	1.99E+00
Photochemical oxidant formation	kg NMVOC	1.39E-02	6.14E-04	2.16E-04	1.47E-02	1.39E-02	6.14E-04	2.16E-04	1.47E-02
Particulate matter formation	kg PM10 eq	1.16E-02	2.62E-04	1.31E-04	1.20E-02	1.16E-02	2.62E-04	1.31E-04	1.20E-02
Terrestrial ecotoxicity	kg 1,4-DB eq	2.20E-04	8.44E-05	3.85E-06	3.09E-04	2.20E-04	8.44E-05	3.85E-06	3.09E-04
Freshwater ecotoxicity	kg 1,4-DB eq	6.15E-02	8.96E-04	1.13E-03	6.35E-02	6.15E-02	8.96E-04	1.13E-03	6.35E-02
Marine ecotoxicity	kg 1,4-DB eq	6.00E-02	1.36E-03	1.01E-03	6.24E-02	6.00E-02	1.36E-03	1.01E-03	6.24E-02
Ionising radiation	kBq U235 eq	1.29E-01	8.77E-03	1.51E-02	1.53E-01	1.29E-01	8.77E-03	1.51E-02	1.53E-01
Agricultural land occupation	m2a	5.77E-02	1.54E-03	3.86E-03	6.31E-02	5.77E-02	1.54E-03	3.86E-03	6.31E-02
Urban land occupation	m2a	3.65E-02	6.18E-03	4.44E-04	4.31E-02	3.65E-02	6.18E-03	4.44E-04	4.31E-02
Natural land transformation	m2	3.53E-04	4.51E-05	1.38E-05	4.12E-04	3.53E-04	4.51E-05	1.38E-05	4.12E-04
Water depletion	m3	6.32E-02	3.77E-04	1.43E-03	6.50E-02	6.32E-02	3.77E-04	1.43E-03	6.50E-02
Metal depletion	kg Fe eq	2.63E+00	4.15E-03	1.37E-03	2.63E+00	2.63E+00	4.15E-03	1.37E-03	2.64E+00
Fossil depletion	kg oil eq	7.14E-01	4.16E-02	2.94E-02	7.85E-01	7.13E-01	4.16E-02	2.94E-02	7.84E-01

Table 33: Reduction coefficients of total impacts between CEM I and CEM II ALL in Robilante plant

Impact category	CEM I	CEM II ALL
Climate change	100	99.19
Ozone depletion	100	99.46
Terrestrial acidification	99.71	100
Freshwater eutrophication	100	99.71
Marine eutrophication	99.99	100
Human toxicity	99.99	100
Photochemical oxidant formation	99.99	100
Particulate matter formation	99.93	100
Terrestrial ecotoxicity	99.99	100
Freshwater ecotoxicity	99.99	100
Marine ecotoxicity	99.99	100
Ionising radiation	99.98	100
Agricultural land occupation	99.99	100
Urban land occupation	99.99	100
Natural land transformation	99.99	100
Water depletion	99.99	100
Metal depletion	99.83	100
Fossil depletion	100	99.89

From Table 33, Figure 53 and Figure 54 significant changes in climate change and ozone depletion are present between CEM I and CEM II ALL being the impacts of CEM II ALL lower for these two categories (99.19% and 99.46%).

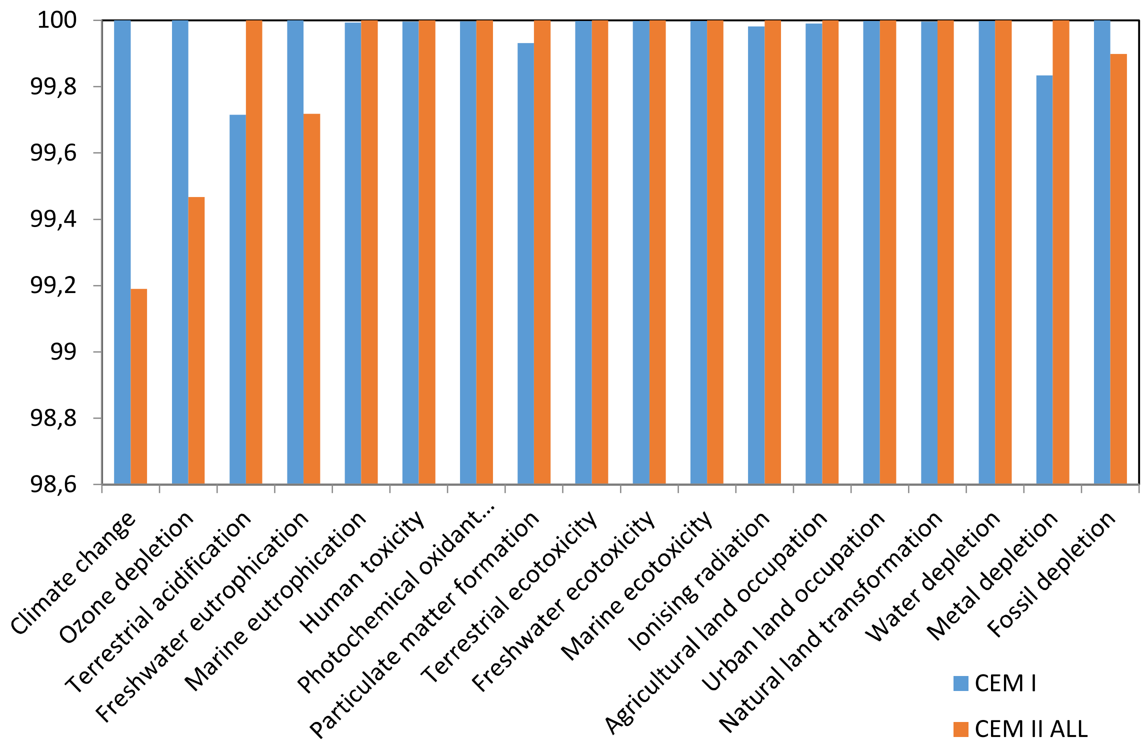

Figure 53: Reduction values of total impacts for Robilante plant

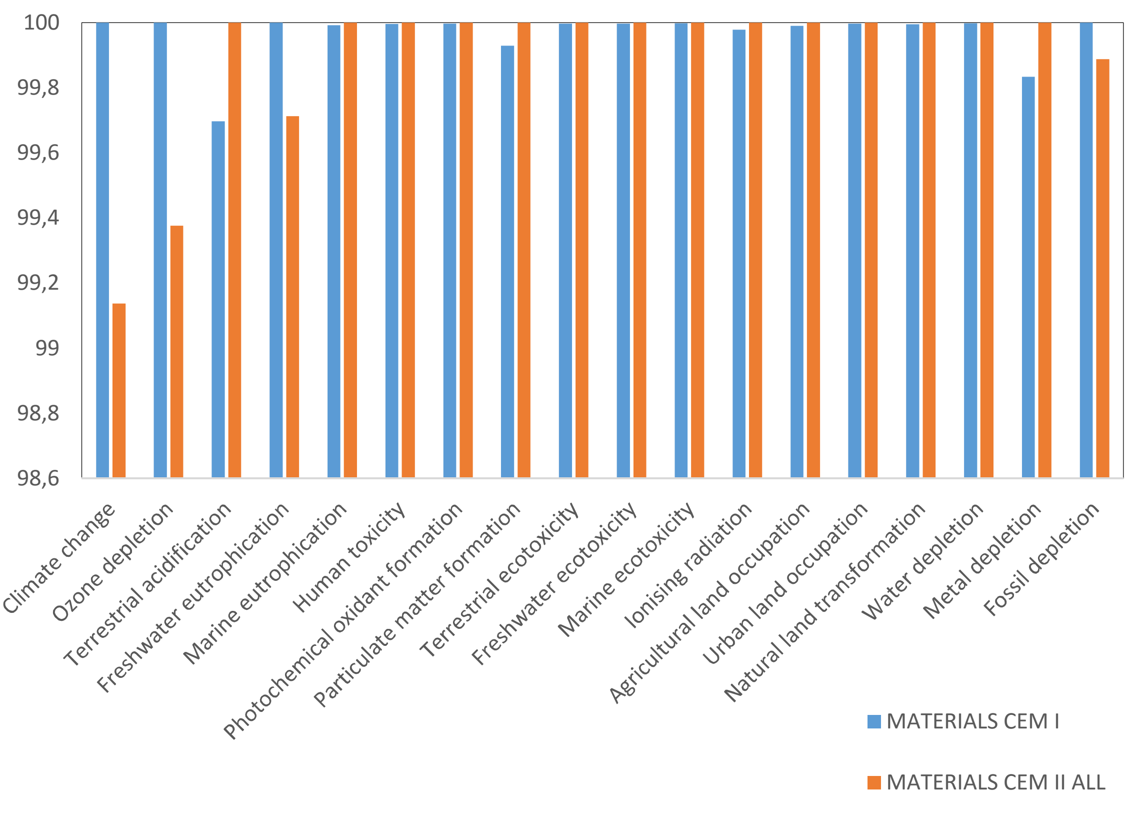

Figure 54: Reduction values of material impacts for Robilante plant

TRINO PLANT

Table 34: Absolute values environmental impacts comparison between cements in Trino plant

		CEM II ALL				CEM IV A V			
Impact category	Unit	MATERIALS	TRANSPORT	LABORATORY	Total	MATERIALS	TRANSPORTS	LABORATORY	Total
Climate change	kg CO2 eq	3.30E+00	1.05E-01	1.04E-01	3.51E+00	3.28E+00	1.05E-01	1.04E-01	3.49E+00
Ozone depletion	kg CFC-11 eq	1.90E-07	2.00E-08	1.00E-08	2.20E-07	1.90E-07	2.00E-08	1.00E-08	2.20E-07
Terrestrial acidification	kg SO2 eq	1.27E-02	4.14E-04	4.00E-04	1.35E-02	1.25E-02	4.14E-04	4.00E-04	1.33E-02
Freshwater eutrophication	kg P eq	1.87E-03	8.67E-06	2.66E-05	1.90E-03	1.86E-03	8.67E-06	2.66E-05	1.90E-03
Marine eutrophication	kg N eq	5.16E-04	2.06E-05	1.40E-05	5.50E-04	5.16E-04	2.06E-05	1.40E-05	5.50E-04
Human toxicity	kg 1,4-DB eq	1.92E+00	4.16E-02	1.98E-02	1.98E+00	1.92E+00	4.16E-02	1.98E-02	1.98E+00
Photochemical oxidant formation	kg NMVOC	1.39E-02	5.62E-04	2.16E-04	1.46E-02	1.39E-02	5.62E-04	2.16E-04	1.46E-02
Particulate matter formation	kg PM10 eq	1.15E-02	2.39E-04	1.31E-04	1.19E-02	1.15E-02	2.39E-04	1.31E-04	1.19E-02
Terrestrial ecotoxicity	kg 1,4-DB eq	2.20E-04	7.72E-05	3.85E-06	3.01E-04	2.20E-04	7.72E-05	3.85E-06	3.01E-04
Freshwater ecotoxicity	kg 1,4-DB eq	6.15E-02	8.19E-04	1.13E-03	6.34E-02	6.15E-02	8.19E-04	1.13E-03	6.34E-02
Marine ecotoxicity	kg 1,4-DB eq	6.00E-02	1.25E-03	1.01E-03	6.23E-02	6.00E-02	1.25E-03	1.01E-03	6.23E-02
Ionising radiation	kBq U235 eq	1.29E-01	8.02E-03	1.51E-02	1.52E-01	1.29E-01	8.02E-03	1.51E-02	1.52E-01
Agricultural land occupation	m2a	5.77E-02	1.41E-03	3.86E-03	6.30E-02	5.77E-02	1.41E-03	3.86E-03	6.30E-02
Urban land occupation	m2a	3.65E-02	5.65E-03	4.44E-04	4.26E-02	3.65E-02	5.65E-03	4.44E-04	4.26E-02
Natural land transformation	m2	3.53E-04	4.12E-05	1.38E-05	4.08E-04	3.53E-04	4.12E-05	1.38E-05	4.08E-04
Water depletion	m3	6.32E-02	3.45E-04	1.43E-03	6.50E-02	6.32E-02	3.45E-04	1.43E-03	6.50E-02
Metal depletion	kg Fe eq	2.63E+00	3.80E-03	1.37E-03	2.63E+00	2.63E+00	3.80E-03	1.37E-03	2.63E+00
Fossil depletion	kg oil eq	7.13E-01	3.80E-02	2.94E-02	7.80E-01	7.12E-01	3.80E-02	2.94E-02	7.80E-01

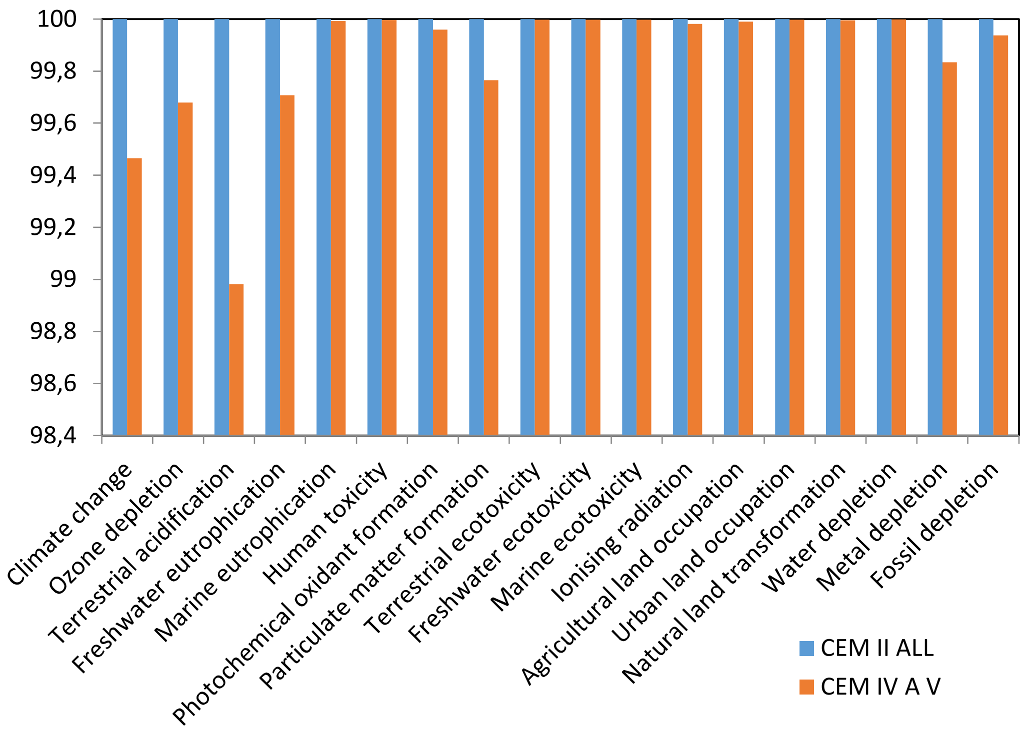

Figure 55: Reduction values of total impacts for Trino plant

In Figure 55 and Figure 56 it can be seen that CEM II ALL has more environmental impacts than CEM IV A V in all categories, especially in terrestrial acidification (almost 99 % for CEM IV A V) .

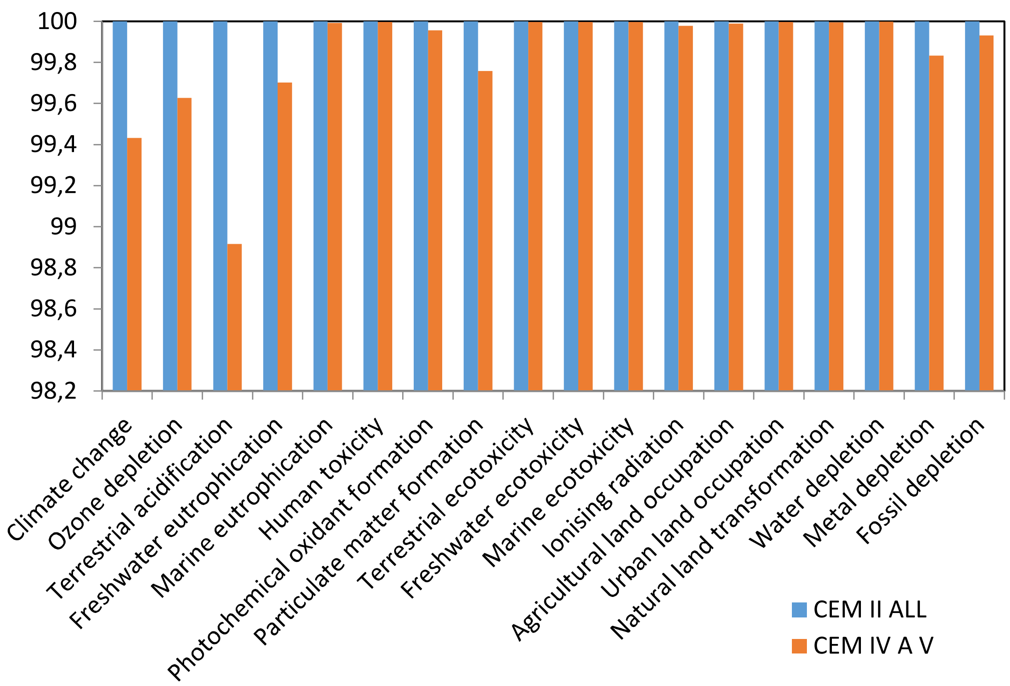

Figure 56: Reduction values of material impacts for Trino plant

VERNASCA PLANT

Table 35: Absolute values environmental impacts comparison between cements in Vernasca plant

		CEM II ALL				CEM IV A V			
Impact category	Unit	MATERIALS	TRANSPORT	LABORATORY	Total	MATERIALS	TRANSPORTS	LABORATORY	Total
Climate change	kg CO2 eq	3.31E+00	1.03E-01	1.04E-01	3.51E+00	3.26E+00	1.03E-01	1.04E-01	3.47E+00
Ozone depletion	kg CFC-11 eq	2.00E-07	2.00E-08	1.00E-08	2.30E-07	1.90E-07	2.00E-08	1.00E-08	2.20E-07
Terrestrial acidification	kg SO2 eq	1.30E-02	4.08E-04	4.00E-04	1.38E-02	1.26E-02	4.08E-04	4.00E-04	1.34E-02
Freshwater eutrophication	kg P eq	1.87E-03	8.55E-06	2.66E-05	1.91E-03	1.85E-03	8.55E-06	2.66E-05	1.89E-03
Marine eutrophication	kg N eq	5.16E-04	2.03E-05	1.40E-05	5.50E-04	5.16E-04	2.03E-05	1.40E-05	5.50E-04
Human toxicity	kg 1,4-DB eq	1.92E+00	4.10E-02	1.98E-02	1.98E+00	1.92E+00	4.10E-02	1.98E-02	1.98E+00
Photochemical oxidant formation	kg NMVOC	1.39E-02	5.55E-04	2.16E-04	1.47E-02	1.39E-02	5.55E-04	2.16E-04	1.46E-02
Particulate matter formation	kg PM10 eq	1.16E-02	2.36E-04	1.31E-04	1.20E-02	1.15E-02	2.36E-04	1.31E-04	1.19E-02
Terrestrial ecotoxicity	kg 1,4-DB eq	2.20E-04	7.62E-05	3.85E-06	3.00E-04	2.20E-04	7.62E-05	3.85E-06	3.00E-04
Freshwater ecotoxicity	kg 1,4-DB eq	6.15E-02	8.09E-04	1.13E-03	6.34E-02	6.15E-02	8.09E-04	1.13E-03	6.34E-02
Marine ecotoxicity	kg 1,4-DB eq	6.00E-02	1.23E-03	1.01E-03	6.23E-02	6.00E-02	1.23E-03	1.01E-03	6.23E-02
Ionising radiation	kBq U235 eq	1.29E-01	7.91E-03	1.51E-02	1.52E-01	1.29E-01	7.91E-03	1.51E-02	1.52E-01
Agricultural land occupation	m2a	5.77E-02	1.39E-03	3.86E-03	6.30E-02	5.77E-02	1.39E-03	3.86E-03	6.30E-02
Urban land occupation	m2a	3.65E-02	5.57E-03	4.44E-04	4.25E-02	3.65E-02	5.57E-03	4.44E-04	4.25E-02
Natural land transformation	m2	3.53E-04	4.07E-05	1.38E-05	4.08E-04	3.53E-04	4.07E-05	1.38E-05	4.08E-04
Water depletion	m3	6.32E-02	3.41E-04	1.43E-03	6.50E-02	6.32E-02	3.41E-04	1.43E-03	6.50E-02
Metal depletion	kg Fe eq	2.63E+00	3.75E-03	1.37E-03	2.63E+00	2.63E+00	3.75E-03	1.37E-03	2.63E+00
Fossil depletion	kg oil eq	7.03E-01	3.75E-02	2.94E-02	7.69E-01	7.03E-01	3.75E-02	2.94E-02	7.69E-01

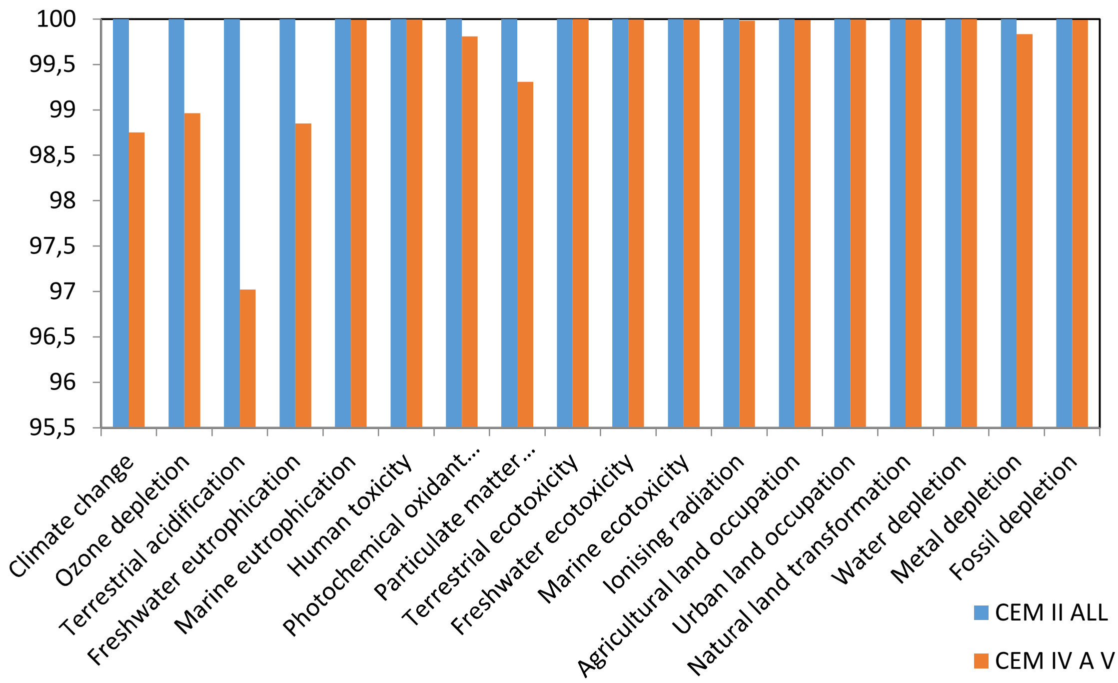

Figure 57: Reduction values of total impacts for Vernasca plant

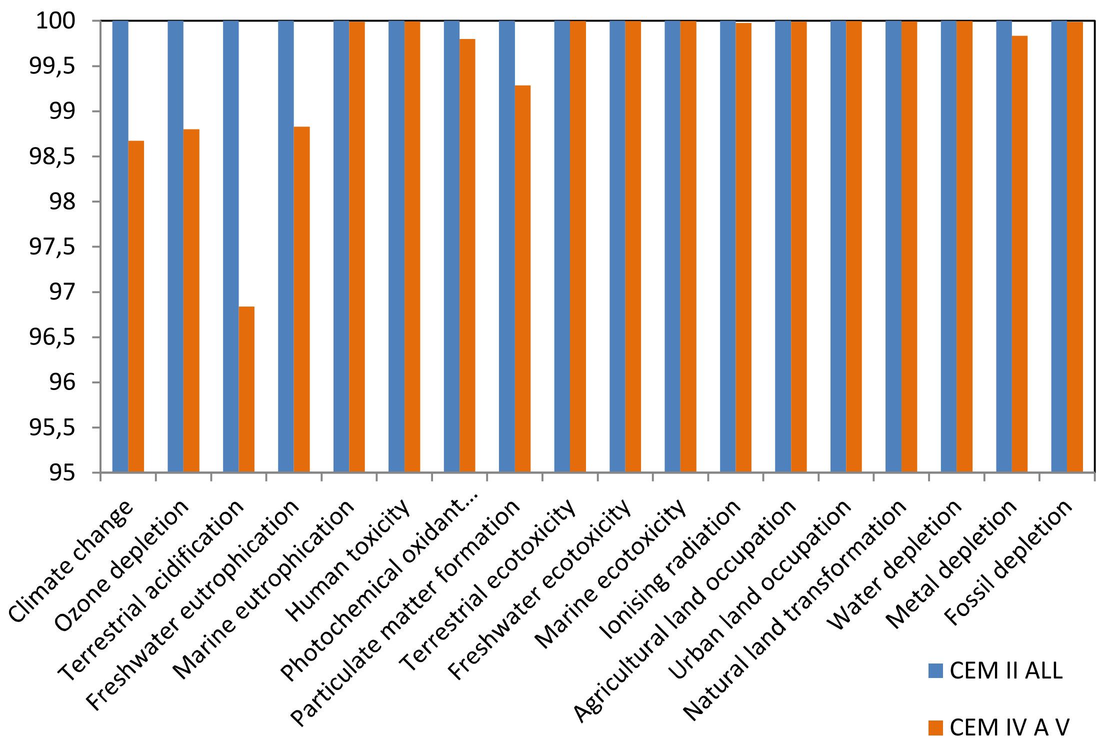

Figure 58: Reduction values of material impacts for Vernasca plant

Also in this case CEM IV A V has lower impacts for all categories and especially terrestrial acidification with almost 97% for material impacts. (See Figure 57 and Figure 58)

GUIDONIA PLANT

Table 36: Absolute values environmental impacts comparison between cements in Guidonia plant

		CEM II ALL				CEM IV A V			
Impact category	Unit	MATERIALS	TRANSPORTS	LABORATORY	Total	MATERIALS	TRANSPORTS	LABORATORY	Total
Climate change	kg CO2 eq	3.33E+00	1.48E-01	1.04E-01	3.59E+00	3.28E+00	1.48E-01	1.04E-01	3.53E+00
Ozone depletion	kg CFC-11 eq	2.00E-07	3.00E-08	1.00E-08	2.40E-07	2.00E-07	3.00E-08	1.00E-08	2.40E-07
Terrestrial acidification	kg SO2 eq	1.32E-02	5.84E-04	4.00E-04	1.42E-02	1.27E-02	5.84E-04	4.00E-04	1.37E-02
Freshwater eutrophication	kg P eq	1.88E-03	1.22E-05	2.66E-05	1.92E-03	1.86E-03	1.22E-05	2.66E-05	1.90E-03
Marine eutrophication	kg N eq	5.16E-04	2.90E-05	1.40E-05	5.59E-04	5.16E-04	2.90E-05	1.40E-05	5.59E-04
Human toxicity	kg 1,4-DB eq	1.92E+00	5.86E-02	1.98E-02	2.00E+00	1.92E+00	5.86E-02	1.98E-02	2.00E+00
Photochemical oxidant formation	kg NMVOC	1.39E-02	7.93E-04	2.16E-04	1.49E-02	1.39E-02	7.93E-04	2.16E-04	1.49E-02
Particulate matter formation	kg PM10 eq	1.16E-02	3.38E-04	1.31E-04	1.21E-02	1.15E-02	3.38E-04	1.31E-04	1.20E-02
Terrestrial ecotoxicity	kg 1,4-DB eq	2.20E-04	1.09E-04	3.85E-06	3.33E-04	2.20E-04	1.09E-04	3.85E-06	3.33E-04
Freshwater ecotoxicity	kg 1,4-DB eq	6.15E-02	1.16E-03	1.13E-03	6.37E-02	6.15E-02	1.16E-03	1.13E-03	6.37E-02
Marine ecotoxicity	kg 1,4-DB eq	6.00E-02	1.76E-03	1.01E-03	6.28E-02	6.00E-02	1.76E-03	1.01E-03	6.28E-02
Ionising radiation	kBq U235 eq	1.29E-01	1.13E-02	1.51E-02	1.56E-01	1.29E-01	1.13E-02	1.51E-02	1.56E-01
Agricultural land occupation	m2a	5.77E-02	1.99E-03	3.86E-03	6.36E-02	5.77E-02	1.99E-03	3.86E-03	6.36E-02
Urban land occupation	m2a	3.65E-02	7.97E-03	4.44E-04	4.49E-02	3.65E-02	7.97E-03	4.44E-04	4.49E-02
Natural land transformation	m2	3.53E-04	5.82E-05	1.38E-05	4.25E-04	3.53E-04	5.82E-05	1.38E-05	4.25E-04
Water depletion	m3	6.32E-02	4.87E-04	1.43E-03	6.51E-02	6.32E-02	4.87E-04	1.43E-03	6.51E-02
Metal depletion	kg Fe eq	2.63E+00	5.36E-03	1.37E-03	2.64E+00	2.63E+00	5.36E-03	1.37E-03	2.63E+00
Fossil depletion	kg oil eq	7.02E-01	5.36E-02	2.94E-02	7.85E-01	7.02E-01	5.36E-02	2.94E-02	7.85E-01

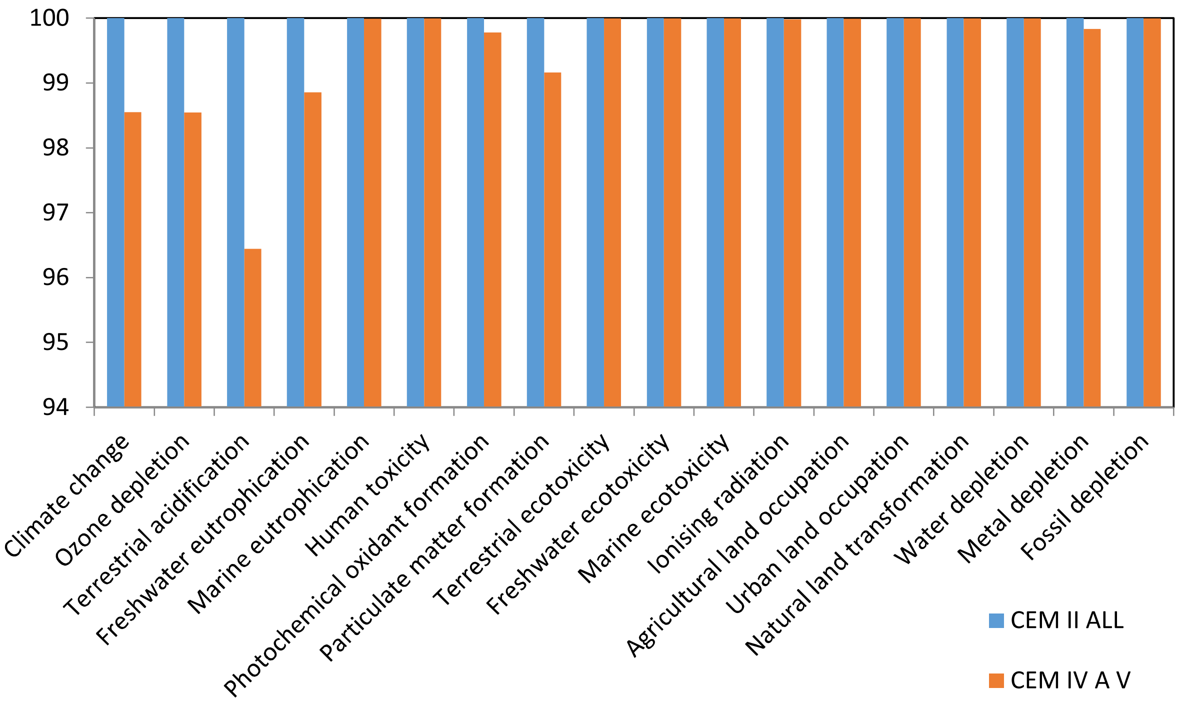

Figure 59: Reduction values of total impacts for Guidonia plant

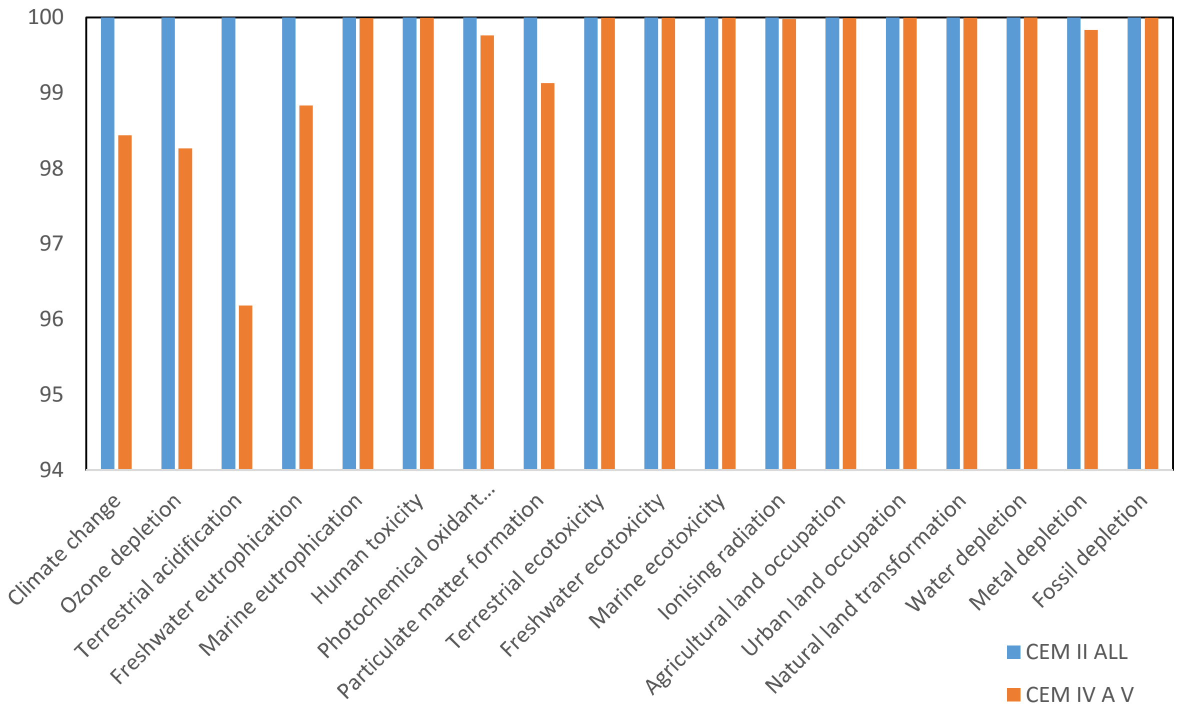

Figure 60: Reduction values of material impacts for Guidonia plant

Again CEM IV has lower impacts for all categories. In this case for terrestrial acidification the percentage is 96%. (See Figure 59 and Figure 60)

AUGUSTA PLANT

Table 37: Absolute values environmental impacts comparison between cements in Augusta plant

		CEM I				CEM II ALL				CEM IV A V			
Impact category	Unit	MATERIALS	TRANSPORTS	LABORATORY	Total	MATERIALS	TRANSPORTS	LABORATORY	Total	MATERIALS	TRANSPORTS	LABORATORY	Total
Climate change	kg CO2 eq	3.35E+00	2.20E-01	1.04E-01	3.67E+00	3.30E+00	2.20E-01	1.04E-01	3.63E+00	3.28E+00	2.20E-01	1.04E-01	3.61E+00
Ozone depletion	kg CFC-11 eq	2.00E-07	4.00E-08	1.00E-08	2.50E-07	2.00E-07	4.00E-08	1.00E-08	2.50E-07	2.00E-07	4.00E-08	1.00E-08	2.50E-07
Terrestrial acidification	kg SO2 eq	1.27E-02	8.67E-04	4.00E-04	1.39E-02	1.27E-02	8.67E-04	4.00E-04	1.39E-02	1.17E-02	8.67E-04	4.00E-04	1.29E-02
Freshwater eutrophication	kg P eq	1.87E-03	1.82E-05	2.66E-05	1.92E-03	1.87E-03	1.82E-05	2.66E-05	1.92E-03	1.87E-03	1.82E-05	2.66E-05	1.91E-03
Marine eutrophication	kg N eq	5.16E-04	4.30E-05	1.40E-05	5.73E-04	5.16E-04	4.30E-05	1.40E-05	5.73E-04	5.16E-04	4.30E-05	1.40E-05	5.73E-04
Human toxicity	kg 1,4-DB eq	1.92E+00	8.70E-02	1.98E-02	2.03E+00	1.92E+00	8.70E-02	1.98E-02	2.03E+00	1.92E+00	8.70E-02	1.98E-02	2.03E+00
Photochemical oxidant formation	kg NMVOC	1.39E-02	1.18E-03	2.16E-04	1.53E-02	1.39E-02	1.18E-03	2.16E-04	1.53E-02	1.38E-02	1.18E-03	2.16E-04	1.52E-02
Particulate matter formation	kg PM10 eq	1.15E-02	5.01E-04	1.31E-04	1.22E-02	1.15E-02	5.01E-04	1.31E-04	1.22E-02	1.13E-02	5.01E-04	1.31E-04	1.20E-02
Terrestrial ecotoxicity	kg 1,4-DB eq	2.20E-04	1.62E-04	3.85E-06	3.86E-04	2.20E-04	1.62E-04	3.85E-06	3.86E-04	2.20E-04	1.62E-04	3.85E-06	3.86E-04
Freshwater ecotoxicity	kg 1,4-DB eq	6.15E-02	1.72E-03	1.13E-03	6.43E-02	6.15E-02	1.72E-03	1.13E-03	6.43E-02	6.15E-02	1.72E-03	1.13E-03	6.43E-02
Marine ecotoxicity	kg 1,4-DB eq	6.00E-02	2.61E-03	1.01E-03	6.36E-02	6.00E-02	2.61E-03	1.01E-03	6.36E-02	6.00E-02	2.61E-03	1.01E-03	6.36E-02
Ionising radiation	kBq U235 eq	1.29E-01	1.68E-02	1.51E-02	1.61E-01	1.29E-01	1.68E-02	1.51E-02	1.61E-01	1.29E-01	1.68E-02	1.51E-02	1.61E-01
Agricultural land occupation	m2a	5.77E-02	2.95E-03	3.86E-03	6.45E-02	5.77E-02	2.95E-03	3.86E-03	6.45E-02	5.77E-02	2.95E-03	3.86E-03	6.45E-02
Urban land occupation	m2a	3.65E-02	1.18E-02	4.44E-04	4.88E-02	3.65E-02	1.18E-02	4.44E-04	4.88E-02	3.65E-02	1.18E-02	4.44E-04	4.88E-02
Natural land transformation	m2	3.53E-04	8.63E-05	1.38E-05	4.53E-04	3.53E-04	8.63E-05	1.38E-05	4.53E-04	3.53E-04	8.63E-05	1.38E-05	4.53E-04
Water depletion	m3												
Metal depletion	kg Fe eq	6.32E-02	7.23E-04	1.43E-03	6.53E-02	6.32E-02	7.23E-04	1.43E-03	6.53E-02	6.32E-02	7.23E-04	1.43E-03	6.53E-02
Fossil depletion	kg oil eq	2.63E+00	7.95E-03	1.37E-03	2.63E+00	2.63E+00	7.95E-03	1.37E-03	2.64E+00	2.63E+00	7.95E-03	1.37E-03	2.63E+00

For Augusta plant it has been done simulations for the three cements. From Figure 61 and Figure 62 it is concluded that CEM IV A V has the less impact in all categories. Between CEM I and CEM II ALL there are differences, CEM II ALL reduces the impacts if compared with CEM I in climate change and ozone depletion (98.72 % and 98.90 % for CEM II ALL, see Table 38:

Table 38: Reduction values of total impacts for Augusta plant

Impact category	CEM I	CEM II ALL	CEM IV A V
Climate change	100	98.72	98.17
Ozone depletion	100	98.90	98.48
Terrestrial acidification	99.99	100	92.89
Freshwater eutrophication	99.99	100	99.70
Marine eutrophication	99.99	100	99.99
Human toxicity	99.99	100	99.99
Photochemical oxidant formation	99.99	100	99.47
Particulate matter formation	99.99	100	98.36
Terrestrial ecotoxicity	99.99	100	99.99
Freshwater ecotoxicity	99.99	100	99.99
Marine ecotoxicity	99.99	100	99.99
Ionising radiation	99.98	100	99.98
Agricultural land occupation	99.99	100	99.99
Urban land occupation	99.99	100	99.99
Natural land transformation	99.99	100	99.99
Water depletion	99.99	100	99.99
Metal depletion	99.83	100	99.83
Fossil depletion	99.99	100	99.99

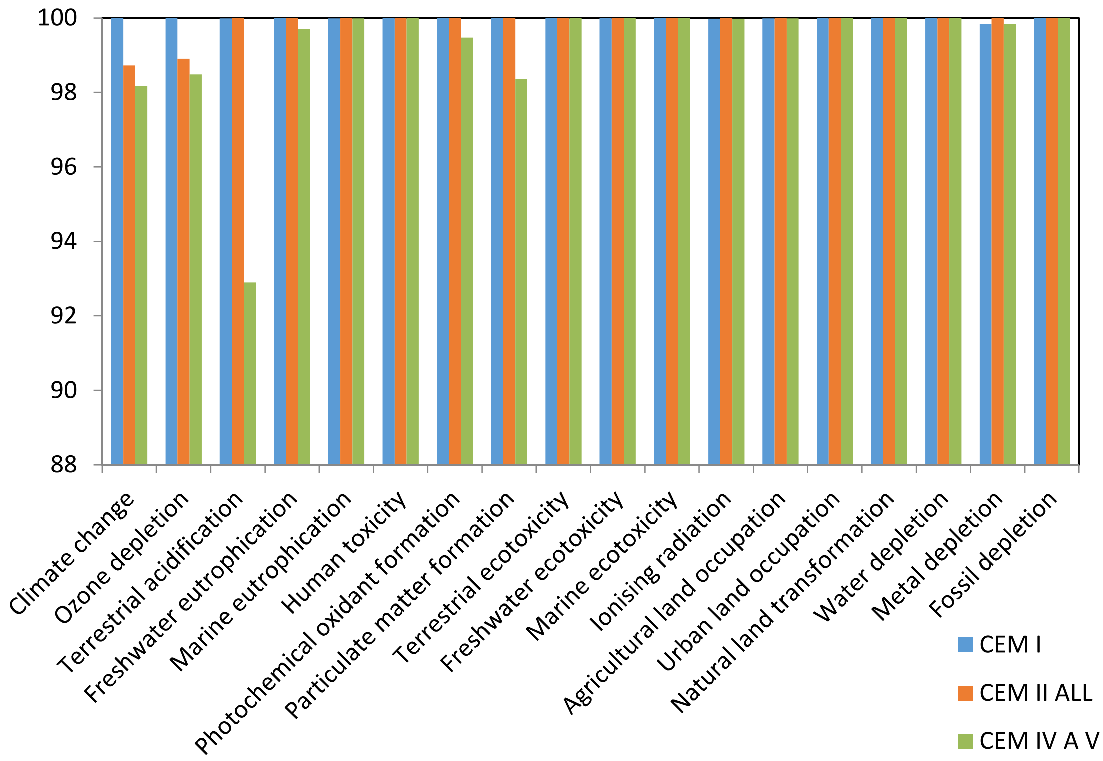

Figure 61: Reduction values of total impacts for Augusta plant

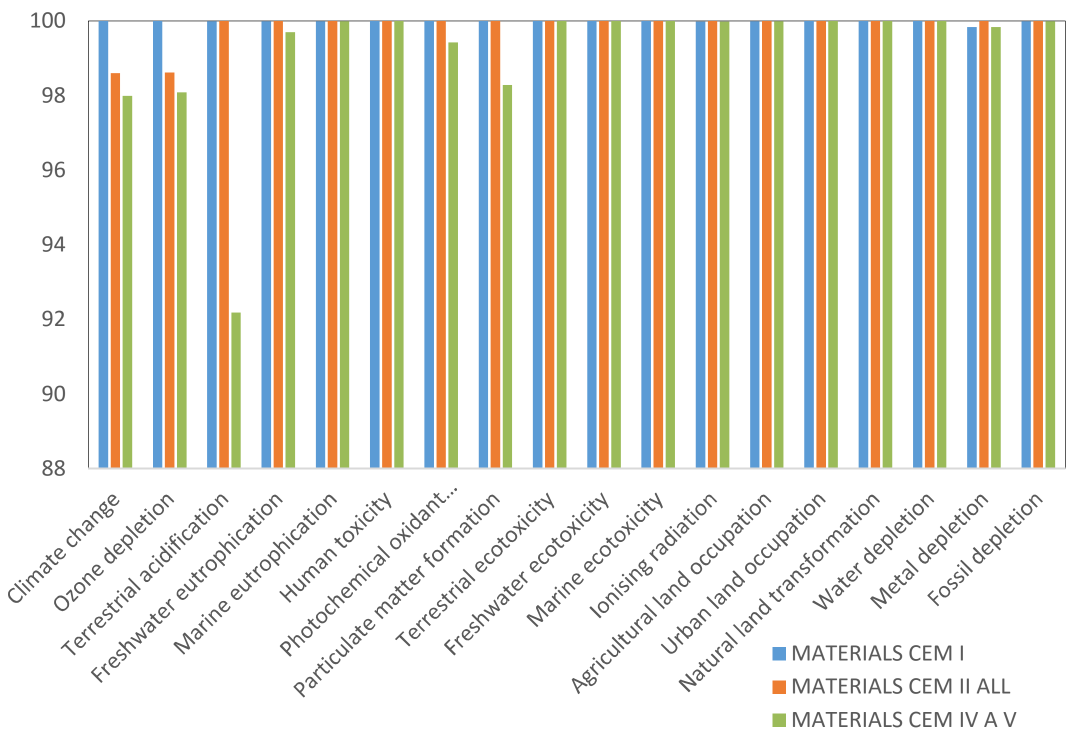

Figure 62: Reduction values of material impacts for Augusta plant

A common behavior of all the scenarios is that:

- Transport phase and laboratory phase are equal for all the cements in the same plant.
- CEM IV A V is the cement which has less impacts.
- CEM I is always more impacting in climate change and ozone depletion categories.

5.2.2 Changing the plant and keeping constant the cement

CEM I

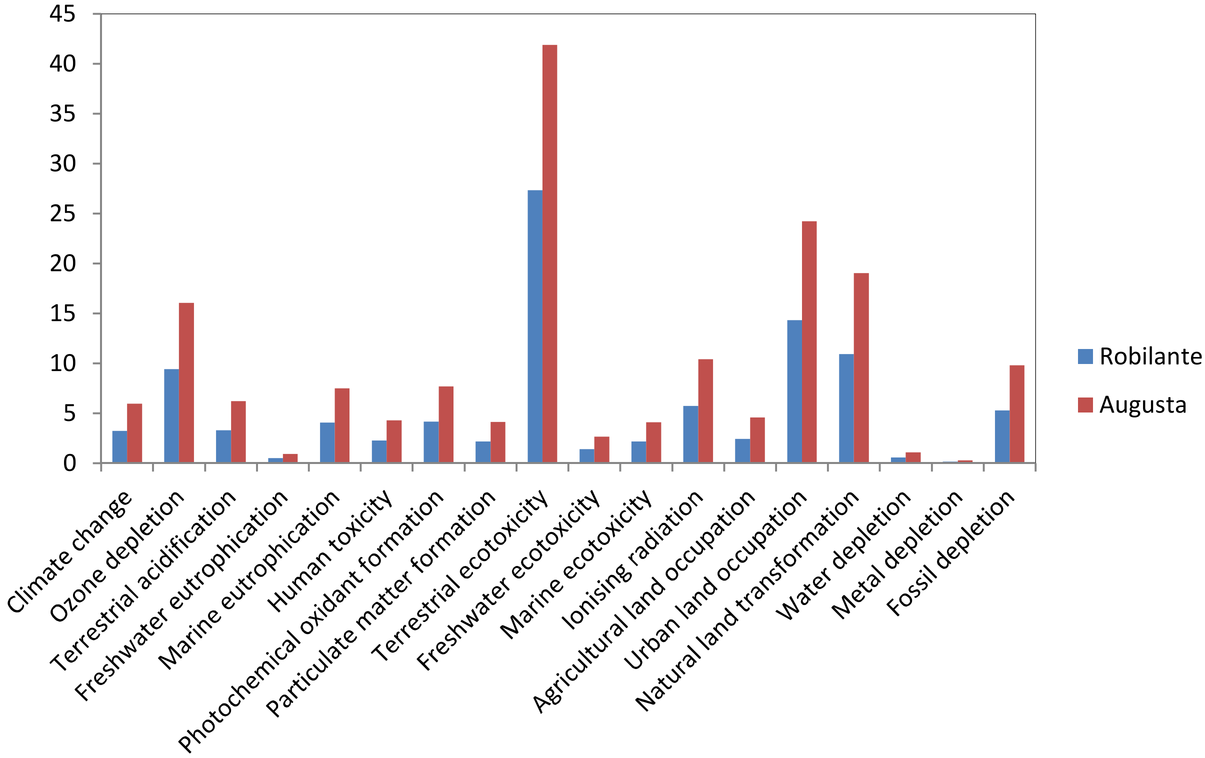

Figure 63: Percentage values transport impacts for CEM I

.

CEM II ALL

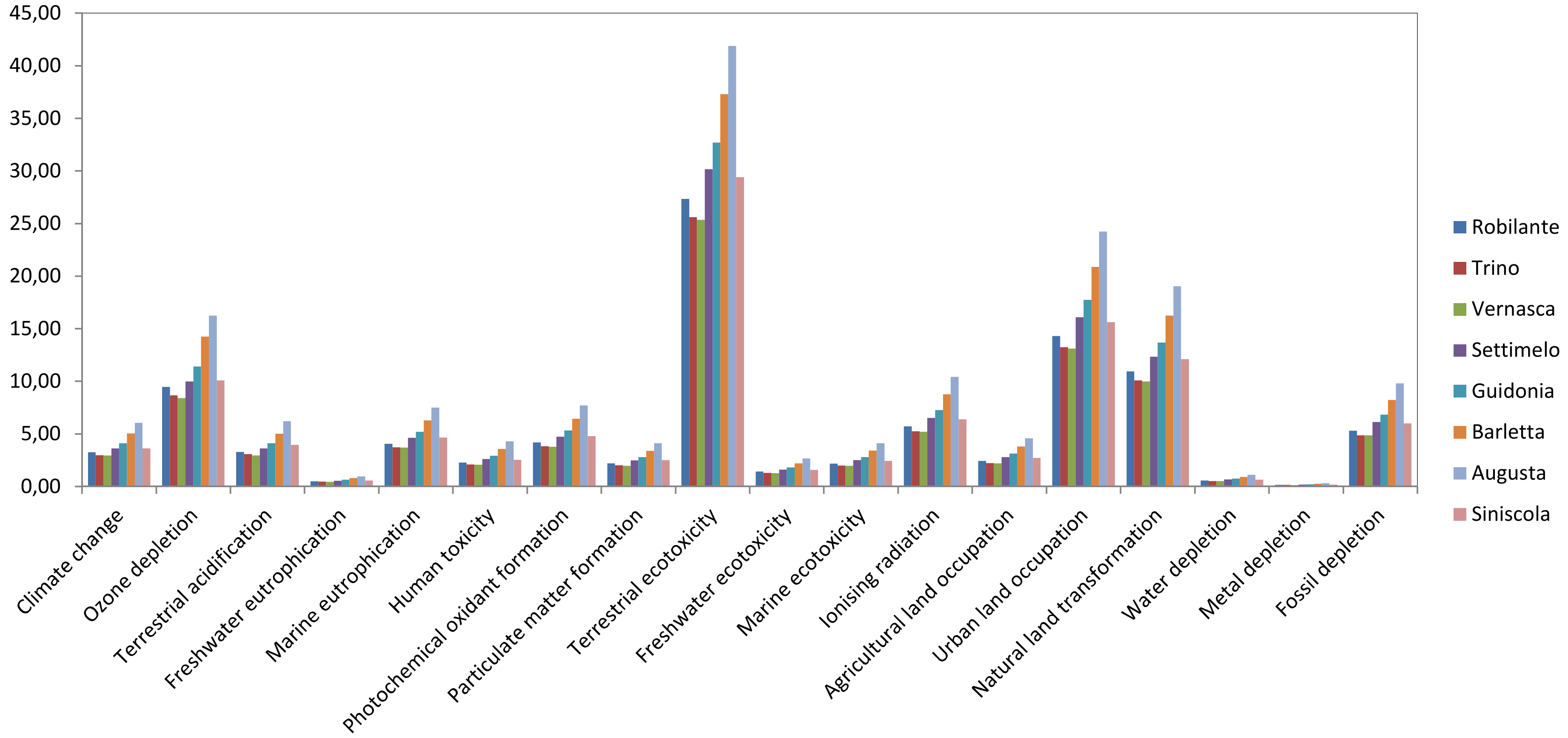

Figure 64: Percentage values transport impacts for CEM II ALL

CEM IV A V

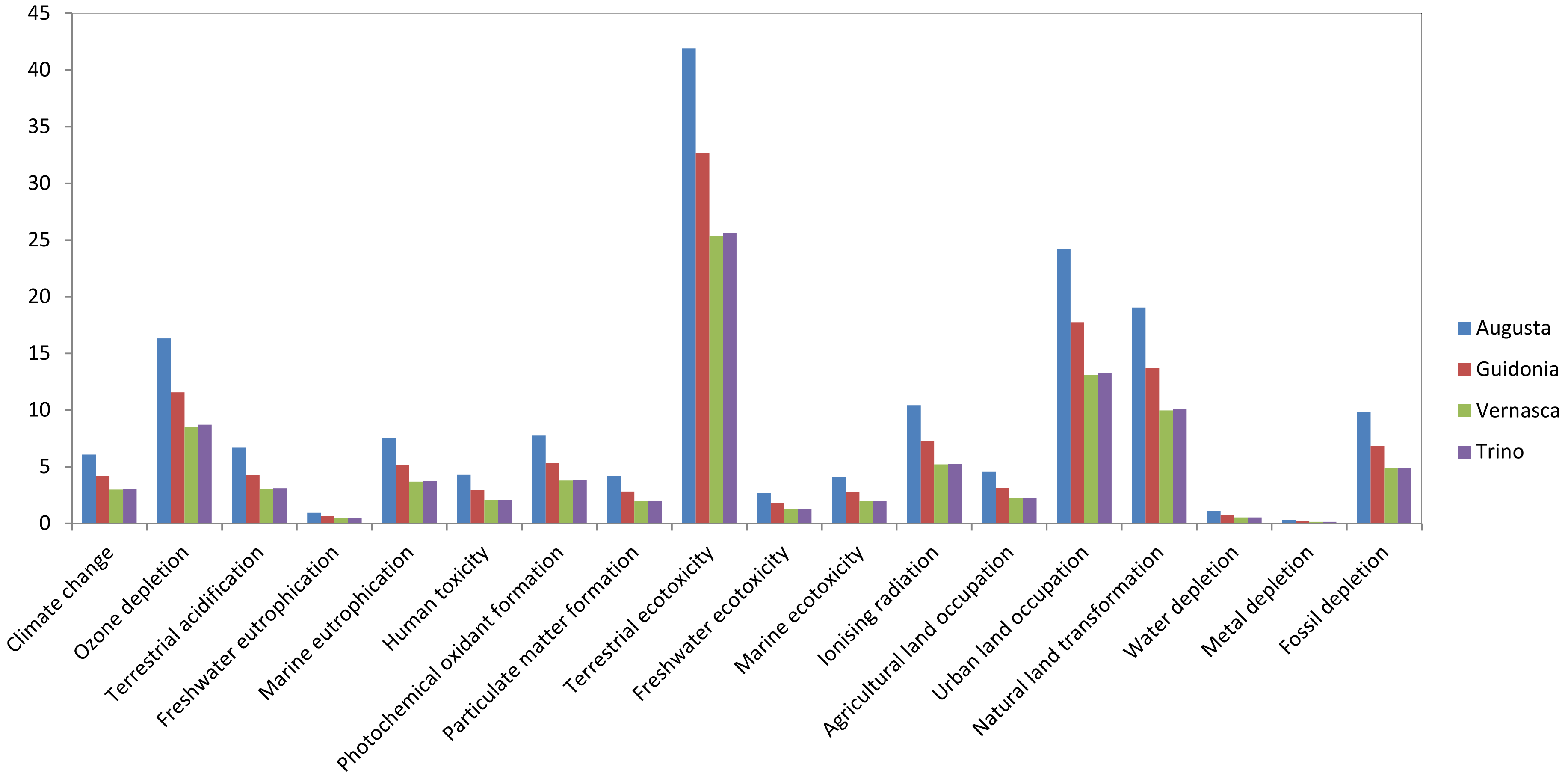

Figure 65: Percentage values transport impacts for CEM IV A V

From Figure 63, Figure 64 and Figure 65 it can be concluded that Augusta plant is the one with more transport impacts being in this case higher than for the simple geometry, 42 % versus 40 % (See Figure 45, Figure 46 and Figure 47).

A normalization is done for Augusta plant as in the case of the simple geometry in order to see which category is more relevant, again Marine ecotoxicity and Freshwater ecotoxicity are the categories which impact the most.

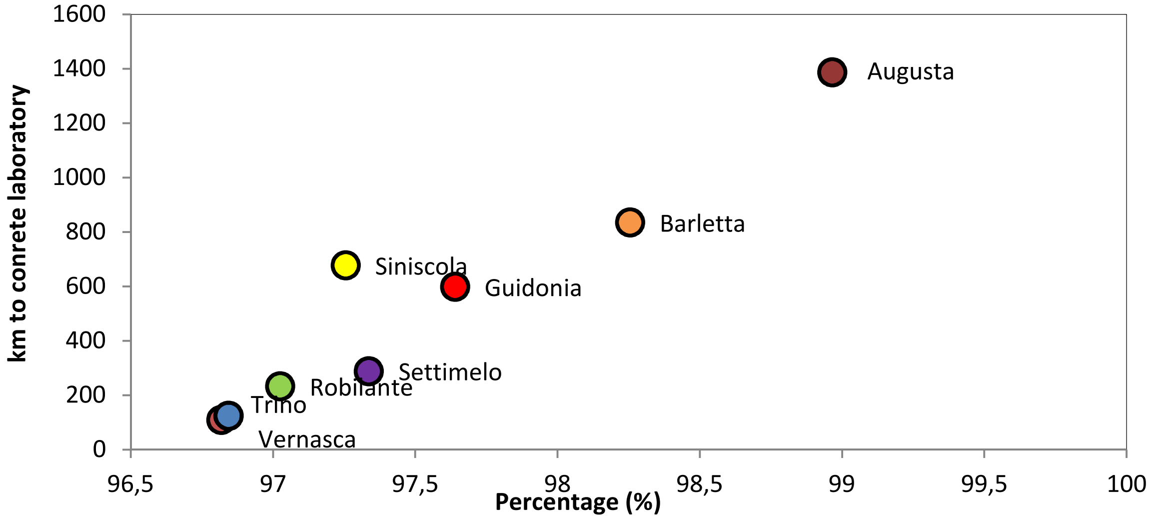

Figure 66: Percentage of global impacts versus kilometers to Concrete Laboratory for Marine ecotoxicity

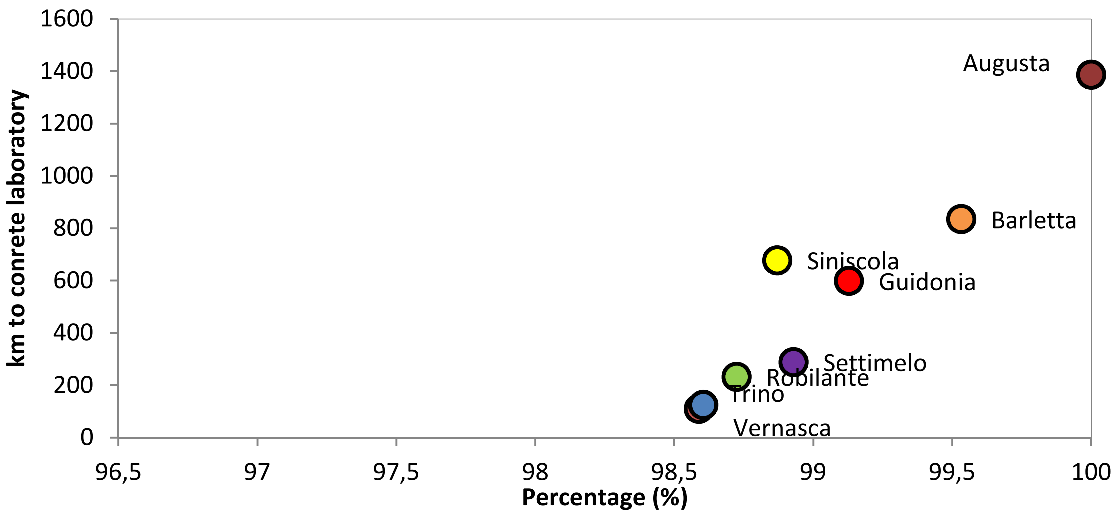

Figure 67: Percentage of global impacts versus kilometers to Concrete Laboratory for Freshwater ecotoxicity

From Figure 66 and Figure 67 it is concluded that the complex geometry behaves in the same manner as the simple geometry as even if the impacts are higher for all categories Augusta is always the plant which gives more impacts and the others are ordered always in the same way.

Therefore, despite both geometries are made with different amounts of materials and their impacts are different the complex geometry confirms the behavior of the simple geometry as disposition of all phases is always de same.

5.3 Comparison of results with the literature

As it can be observed in the following Table 39, the assumptions made before starting with the simulation led to results which are confimed with the literature:

- Cradle-to-gate variant was chosen as most of the articles adopted this way.

- CEM I (Portland cement) is the most impacting cement both in this study and in all the articles found (Michael W.Tait et al, 2016; Nicolas Serres et al, 2015; Janez Turk et al, 2015; Deborah N. Huntzinger et al, 2009).

- CEM IV A-V (Pozzolanic cement) is the less impacting cement in this study and also in (Deborah N. Huntzinger et al, 2009).

- ReCiPe midpoint was the approach adopted in the study as it was gave good results in (Ya Hong Dong et al, 2015) and was defined as an approach that provides reliable while the endpoint approach gives additional information of damage with a higher degree of interpretation.

Table 39: Comparison of results with articles from literature

	AIM	VARIABLES	MATERIALS	BOUNDARIES	IMPACT ASSESSMENT METHOD	FUNCTIONAL UNIT
Present study	Comparing RC specimens	Cement type and distance to the cement plant	CEM I, CEM II ALL, CEM IV A V (42.5R) Limestone Reinforced steel	Cradle-to-gate	Recipe midpoint H	1 specimen
(G. Habert et al, 2012)	Lowering global warming or a bridge rehabilitation	Different Ultra-High Performance Fibre Reinforced Concretes	UHPFRC ECO-UHPFRC	Cradle-to-gate	Global Warming Potential	one bridge
(Michael W.Tait et al, 2016)	Comparing concrete specimens	Concrete mix design	CEM I CEM II B-V CEM III/B	Cradle-to-gate	EcoIndicator-99 EDP 2008 Ecopoints 97	1 m^3 of concrete
(Nicolas Serres et al, 2015)	Comparing traditional and recycled mix designs	Concrete mix designs	Traditional mix design Mixed mix design Recycled mix design CEM I	Cradle-to-gate	EPD method (Endpoint) CML method Environmental design of Industrial Products (EDIP) Building for Environmental and Economic Sustainability (BEES)	1 m^3 of concrete
(Janez Turk et al, 2015)	Comparing conventional and green concretes	Concrete mix designs	Foundry sand as aggregate Steel slag as aggregate Fly ash as aggregate Portland cement	Cradle-to-gate	Global warming potential Abiotic Resource Depletion of Fossil fuels Acidification Potential	1 m^3 of concrete
(Deborah N. Huntzinger et al, 2009)	Comparing the traditional Portland process with other technologies	Type of cement	Portland cement Pozzolanic cement Cement with recycled kiln dust	Cradle-to-gate	Building for Environmental and Economic Sustainability (BEES)	1 ton of cement
(Ya Hong Dong et al, 2015)	Comparing the midpoint and endpoint approaches based on ReCiPe	Approaches based on ReCiPe	23 different types of construction materials	Cradle-to-grave	ReCiPe midpoint method	1 m^3 of concrete

Comparison between simulations made using EPD data and real primary data

As it was explained in Chapter 4, data of cements in Chapter 5 was derived from the EPD (Environmental Product Declaration) provided by Buzzi Unicem. In that case data from emissions to water and emissions to soil were used to identify each type of cement and made possible to develop the simulations.

On the other hand, in this Chapter data from EPD is not used. Real data for a specific type of cement CEM II ALL produced in Trino plant was provided by Buzzi. In this case the simulations are not performed based on the emissions produced cements in previous studies, simulations are performed based on real primary data of materials, energy and transport needed for the production of CEM II ALL.

6.1 Methodology

In order to produce CEM II ALL in Trino plant several materials, fuels and electricity are needed as it can be seen in the following Table 40. All of them are data obtained from database Ecoinvent except clinker, which is also real primary data. Composition of clinker is summarised in Table 41.

Table 40: Materials/Fuels and Electricity/Heat required for the production of CEM II ALL in Trino plant

Materials/fuels	Amount	Unit
Clinker in Robilante	822.93	kg
Electrofilter dust recycling from white clinker raw material production U/I S	24.16	kg
Iron Sulphate monohydrate from Titanium dioxide sulphate Romania U/I S	0.38	kg
Chemicals inorganic, at plant/GLO S	0.59	kg
Chemicals organic, at plant/GLO S	0.88	kg
Calcium Sulphate from Hydrofluoric Acid production U/I S	1.84	kg
Limestone, at mine/CH S	91.73	kg
Gypsum, mineral, at mine/I U Sistema	42.65	kg
Pozzolana, at mine/I U S	13.94	kg
Gypsum from desulfurization CODICE CER 10.01.05	12.23	kg
Transport, lorry 16-32t, EURO3/RER S	37.04	tkm
Transport, lorry 16-32t, EURO3/RER S	8.7	tkm
Transport, lorry 16-32t, EURO3/RER S	151.09	tkm
Transport, lorry 16-32t, EURO3/RER S	3.06	tkm
Kraft paper, unbleached, at plant/RER S	0.366	kg
Transport, lorry 16-32t, EURO3/RER S	0.015	tkm
Transport, lorry 16-32t, EURO3/RER S	0	tkm
EUR-flat pallet/RER S	0.0384	p
Transport, lorry 16-32t, EURO3/RER S	0.0416	tkm
Transport, lorry 16-32t, EURO3/RER S	0.0019	tkm
Packaging film, LDPE, at plant/RER S	0.014	kg
Transport, lorry 16-32t, EURO3/RER S	0.0014	tkm
Transport, lorry 16-32t, EURO3/RER S	0	tkm
Operation, freight train/IT S	95.79	tkm
Electricity/heat		
Electricity, high voltage, at grid/IT S	26.92	kWh
Natural gas, burned in boiler modulating <100kW/RER S W/O CO2 FOR CEMENT SECTOR Sistema	5.54	MJ
Diesel, at refinery/RER S	0.12	kg

Table 41: Resources, Materials/Fuels, Electricity/Heat required for the production of Clinker

Resources	Amount	Unit
Water, groundwater consumption	376.61	kg
Materials/fuels		
Limestone, at mine/CH S	1173.67	kg
Clay, at mine/CH S	367.64	kg
Iron ore, 46% Fe, at mine/GLO S	18.15	kg
Silica sand, at plant/I U Sistema	1.85	kg
Bauxite, at mine/GLO S	2.69	kg
Soluzione Ammoniacale < 25% U Sistema	2.64	kg
Scaglie da laminazione CODICE CER 10.02.10	0.25	kg
Fanghi trattamento acque	0.35	kg
Refractory, basic, packed, at plant/I U Sistema	1.26	kg
Sodium carbonate from ammonium chloride production, at plant/GLO S	0.002	kg
Transport, lorry 3.5-16t, fleet average/RER S	4.76	tkm
Transport, lorry 16-32t, EURO3/RER S	20.22	tkm
Transport, lorry 16-32t, EURO3/RER S	0.04	tkm
Transport, lorry 16-32t, EURO3/RER S	4.57	tkm
Transport, lorry 16-32t, EURO3/RER S	1.481	tkm
Transport, lorry 16-32t, EURO3/RER S	28.24	tkm
Transport, transoceanic freight ship/OCE S	729.62	tkm
Electricity/heat		
Electricity, high voltage, at grid/IT S	60.7564	kWh
Electricity, high voltage, at grid/IT S	13.9858	kWh
Petroleum coke, at refinery/RER S	63.1	kg
Hard coal, at regional storage/EEU S	14.8	kg
PRODUZIONE CDR U/I S	59.017	kg
Heavy fuel oil, at refinery/RER S	0.0003	ton
Diesel, at refinery/RER S	0.0473	kg
Light fuel oil, burned in boiler 100kW, non-modulating/IT S W/O CO2 FOR CEMENT SECTOR Sistema	0.01	MJ

6.2 Comparison between simulations using EPD data and real primary data from Buzzi Unicem

As it was said previously simulations using both types of primary data were made for the simple and also for the more complex reinforced concrete structure. The cement used is CEM II ALL produced in Trino.

6.2.1 Comparison between simulations using EPD data and real primary primary data from Buzzi Unicem for a simple reinforced concrete bar specimen

Simulations were performed in the same way as they were made in Chapter 5. Environmental impacts obtained from both simulations are showed in the following Table 42.

From Table 42 it can be seen that the transport and laboratory phase does not change as it was expected as the cement is the only variable in this study. For this reason, the materials phase is the only one that varies but its changes are not significant, they are very small. However, reduction values of materials phase are represented in Table 43 and Figure 68.

As it can be seen from the reduction values, it is confirmed that the variations between these two scenarios are not significant as they are in the order of 81% in the case of natural land transfomation to almost 100% in the case of metal depletion.

Table 42: Absolute values environmental impacts comparison between CEM II ALL from EPD data and from real primary data produced in Trino plant for a simple reinforced concrete bar specimen

		CEM II ALL from EPD data				CEM II ALL from real primary data			
Impact category	Unit	MATERIALS	TRANSPORTS	LABORATORY	Total	MATERIALS	TRANSPORTS	LABORATORY	Total
Climate change	kg CO2 eq	6.21E-01	2.01E-02	1.04E-01	7.45E-01	5.49E-01	2.01E-02	1.04E-01	6.73E-01
Ozone depletion	kg CFC-11 eq	3.60E-08	3.69E-09	1.16E-08	5.14E-08	3.58E-08	3.69E-09	1.16E-08	5.11E-08
Terrestrial acidification	kg SO2 eq	2.38E-03	7.91E-05	4.00E-04	2.86E-03	2.29E-03	7.91E-05	4.00E-04	2.77E-03
Freshwater eutrophication	kg P eq	3.51E-04	1.66E-06	2.66E-05	3.79E-04	3.21E-04	1.66E-06	2.66E-05	3.49E-04
Marine eutrophication	kg N eq	9.66E-05	3.93E-06	1.40E-05	1.15E-04	9.97E-05	3.93E-06	1.40E-05	1.18E-04
Human toxicity	kg 1,4-DB eq	3.60E-01	7.95E-03	1.98E-02	3.87E-01	3.60E-01	7.95E-03	1.98E-02	3.88E-01
Photochemical oxidant formation	kg NMVOC	2.60E-03	1.07E-04	2.16E-04	2.92E-03	2.66E-03	1.07E-04	2.16E-04	2.99E-03
Particulate matter formation	kg PM10 eq	2.16E-03	4.58E-05	1.31E-04	2.34E-03	2.17E-03	4.58E-05	1.31E-04	2.34E-03
Terrestrial ecotoxicity	kg 1,4-DB eq	4.13E-05	1.48E-05	3.85E-06	5.99E-05	4.21E-05	1.48E-05	3.85E-06	6.07E-05
Freshwater ecotoxicity	kg 1,4-DB eq	1.15E-02	1.57E-04	1.13E-03	1.28E-02	1.15E-02	1.57E-04	1.13E-03	1.28E-02
Marine ecotoxicity	kg 1,4-DB eq	1.12E-02	2.38E-04	1.01E-03	1.25E-02	1.13E-02	2.38E-04	1.01E-03	1.25E-02
Ionising radiation	kBq U235 eq	2.42E-02	1.53E-03	1.51E-02	4.09E-02	2.63E-02	1.53E-03	1.51E-02	4.30E-02
Agricultural land occupation	m2a	1.08E-02	2.69E-04	3.86E-03	1.49E-02	1.17E-02	2.69E-04	3.86E-03	1.58E-02
Urban land occupation	m2a	6.84E-03	1.08E-03	4.44E-04	8.36E-03	6.99E-03	1.08E-03	4.44E-04	8.51E-03
Natural land transformation	m2	6.61E-05	7.88E-06	1.38E-05	8.79E-05	8.13E-05	7.88E-06	1.38E-05	1.03E-04
Water depletion	m3	1.18E-02	6.60E-05	1.43E-03	1.33E-02	1.22E-02	6.60E-05	1.43E-03	1.37E-02
Metal depletion	kg Fe eq	4.92E-01	7.26E-04	1.37E-03	4.95E-01	4.93E-01	7.26E-04	1.37E-03	4.95E-01
Fossil depletion	kg oil eq	1.34E-01	7.27E-03	2.94E-02	1.70E-01	1.44E-01	7.27E-03	2.94E-02	1.80E-01

Table 43: Reduction values of material impacts for CEM II ALL produced in Trino plant for a simple reinforced concrete bar specimen

Impact category	CEM II ALL from EPD	CEM II ALL from real primary data provided by Buzzi
Climate change	100.00	88.38
Ozone depletion	100.00	99.30
Terrestrial acidification	100.00	96.10
Freshwater eutrophication	100.00	91.56
Marine eutrophication	96.84	100.00
Human toxicity	99.80	100.00
Photochemical oxidant formation	97.46	100.00
Particulate matter formation	99.76	100.00
Terrestrial ecotoxicity	98.00	100.00
Freshwater ecotoxicity	99.81	100.00
Marine ecotoxicity	99.72	100.00
Ionising radiation	91.89	100.00
Agricultural land occupation	92.71	100.00
Urban land occupation	97.86	100.00
Natural land transformation	81.33	100.00
Water depletion	97.01	100.00
Metal depletion	99.92	100.00
Fossil depletion	92.97	100.00

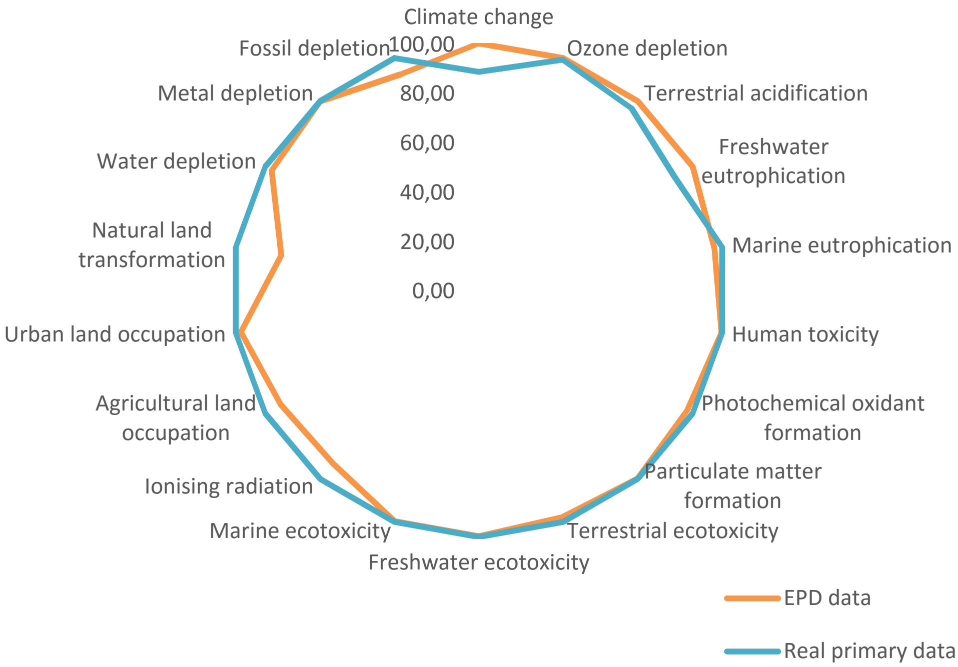

Figure 68: Reduction values for material impacts of CEM II ALL produced in Trino plant for a simple reinforced concrete bar specimen

6.2.2 Comparison between simulations using EPD data and real primary primary data from Buzzi Unicem for a complex reinforced concrete structure

The environmental impacts results of the simulation made for the case of a complex reinforced concrete structure can be seen in the following Table 44. As in the previous case transport and laboratory phase does not change. Material changes are not significant and they are showed in Table 45 and Figure 69.

Also in this case it is confirmed the insignificant changes as the reduction values range from 82% in natural land transformation to almost 100% in the case of metal depletion.

Table 44: Absolute values environmental impacts comparison between CEM II ALL from EPD data and from real primary data produced in Trino plant for a complex reinforced concrete structure

		CEM II ALL from EPD data				CEM II ALL from real primary data			
Impact category	Unit	MATERIALS	TRANSPORTS	LABORATORY	Total	MATERIALS	TRANSPORTS	LABORATORY	Total
Climate change	kg CO2 eq	3.30E+00	1.05E-01	1.04E-01	3.51E+00	2.93E+00	1.05E-01	1.04E-01	3.14E+00
Ozone depletion	kg CFC-11 eq	1.92E-07	1.93E-08	1.16E-08	2.23E-07	1.90E-07	1.93E-08	1.16E-08	2.21E-07
Terrestrial acidification	kg SO2 eq	1.27E-02	4.14E-04	4.00E-04	1.35E-02	1.22E-02	4.14E-04	4.00E-04	1.30E-02
Freshwater eutrophication	kg P eq	1.87E-03	8.67E-06	2.66E-05	1.90E-03	1.72E-03	8.67E-06	2.66E-05	1.75E-03
Marine eutrophication	kg N eq	5.16E-04	2.06E-05	1.40E-05	5.50E-04	5.32E-04	2.06E-05	1.40E-05	5.66E-04
Human toxicity	kg 1,4-DB eq	1.92E+00	4.16E-02	1.98E-02	1.98E+00	1.92E+00	4.16E-02	1.98E-02	1.99E+00
Photochemical oxidant formation	kg NMVOC	1.39E-02	5.62E-04	2.16E-04	1.46E-02	1.42E-02	5.62E-04	2.16E-04	1.50E-02
Particulate matter formation	kg PM10 eq	1.15E-02	2.39E-04	1.31E-04	1.19E-02	1.16E-02	2.39E-04	1.31E-04	1.19E-02
Terrestrial ecotoxicity	kg 1,4-DB eq	2.20E-04	7.72E-05	3.85E-06	3.01E-04	2.25E-04	7.72E-05	3.85E-06	3.06E-04
Freshwater ecotoxicity	kg 1,4-DB eq	6.15E-02	8.19E-04	1.13E-03	6.34E-02	6.16E-02	8.19E-04	1.13E-03	6.35E-02
Marine ecotoxicity	kg 1,4-DB eq	6.00E-02	1.25E-03	1.01E-03	6.23E-02	6.02E-02	1.25E-03	1.01E-03	6.24E-02
Ionising radiation	kBq U235 eq	1.29E-01	8.02E-03	1.51E-02	1.52E-01	1.40E-01	8.02E-03	1.51E-02	1.63E-01
Agricultural land occupation	m2a	5.77E-02	1.41E-03	3.86E-03	6.30E-02	6.21E-02	1.41E-03	3.86E-03	6.74E-02
Urban land occupation	m2a	3.65E-02	5.65E-03	4.44E-04	4.26E-02	3.73E-02	5.65E-03	4.44E-04	4.34E-02
Natural land transformation	m2	3.53E-04	4.12E-05	1.38E-05	4.08E-04	4.31E-04	4.12E-05	1.38E-05	4.86E-04
Water depletion	m3	6.32E-02	3.45E-04	1.43E-03	6.50E-02	6.51E-02	3.45E-04	1.43E-03	6.68E-02
Metal depletion	kg Fe eq	2.63E+00	3.80E-03	1.37E-03	2.63E+00	2.63E+00	3.80E-03	1.37E-03	2.64E+00
Fossil depletion	kg oil eq	7.13E-01	3.80E-02	2.94E-02	7.80E-01	7.65E-01	3.80E-02	2.94E-02	8.32E-01

Table 45: Reduction values of material impacts for CEM II ALL produced in Trino plant for a complex reinforced concrete structure

Impact category	CEM II ALL from EPD	CEM II ALL from real primary data provided by Buzzi
Climate change	100.00	88.73
Ozone depletion	100.00	99.10
Terrestrial acidification	100.00	96.23
Freshwater eutrophication	100.00	91.83
Marine eutrophication	96.95	100.00
Human toxicity	99.81	100.00
Photochemical oxidant formation	97.55	100.00
Particulate matter formation	99.77	100.00
Terrestrial ecotoxicity	98.07	100.00
Freshwater ecotoxicity	99.81	100.00
Marine ecotoxicity	99.73	100.00
Ionising radiation	92.15	100.00
Agricultural land occupation	92.94	100.00
Urban land occupation	97.93	100.00
Natural land transformation	81.86	100.00
Water depletion	97.11	100.00
Metal depletion	99.92	100.00
Fossil depletion	93.20	100.00

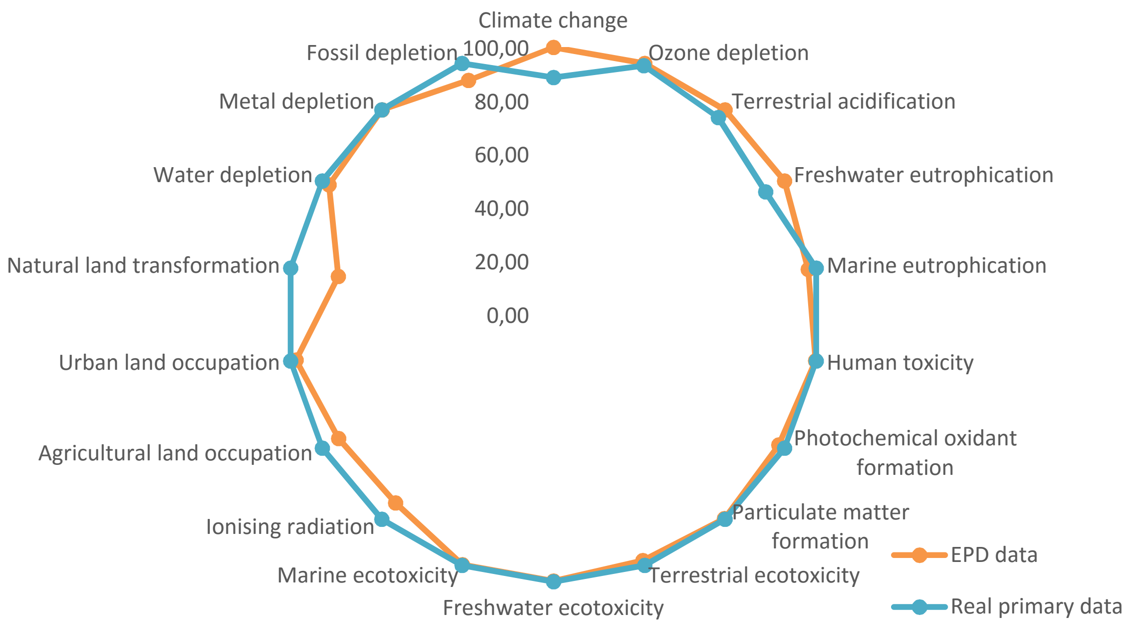

Figure 69: Reduction values of material impacts for CEM II ALL produced in Trino plant for a complex reinforced concrete structure

6.3 Errors

Although the changes between the cements CEM II ALL produced with data provided from EPD and real primary data from Buzzi are so small there is a certain error which depends on the categories and ranges from 0.001 % in the case of metal depletion to 18 % in the case of natural land transformation.

The main cause of these errors can be due to the modification of values on the database of SimaPro. The real primary data provided materials which were modified by Buzzi and were not specified so such variations were not taken into account and standard data from database was used.

Conclusions

The aim of this study was to evaluate the environmental impacts of two reinforced concrete structures using several cements with the same compression resistance 42.5R, CEM I, CEM II ALL and CEM IV A V produced in different plants of Italy. The order of these plants regarding the distance to the Concrete Laboratory in Via Mancinelli is Vernasca, Trino, Robilante, Settimelo, Guidonia, Siniscola, Barletta and Augusta.

The first step was to compare the cements in each particular plant. The results obtained from the simulation showed that the materials phase is the phase which gives more significant differences as the variable is the type of cement while the transport and the laboratory phase are invariable. In addition it was showed that CEM IV A V is the cement which gives lower environmental impacts in all scenarios, this result coincides with the result obtained in (Deborah N. Huntzinger et al, 2009) in which blended cements (natural pozzolanic) had the greater environmental savings. Moreover, it is also confirmed with (Michael W. Tait et al, 2016) and (Janez Turk, 2015), articles that state that CEM I (Portland cement) is the one with higher environmental impacts.

Furthermore, the environmental impacts given by CEM I and CEM IL ALL depend on the different categories. Evaluating the reduction values for each category it can be concluded that the most significant differences are seen in climate change and ozone depletion categories being CEM II ALL the one which minimises its impacts. The reduction values for these two categories are of about 2% while the ones for which CEM I has lower impacts are of abour 0.01% being considered totally insignificant.

The following step was to compare for each type of cement the transport impacts of all the different cement suppliers. This evaluation has a common behaviour for the three types of cements. As it is not surprising, the transport impacts increase with the distance being Augusta the plant which gives more impacts and so the one less favourable to be the cement supplier. For this reason, Vernasca or Trino are the chosen plants to minimise the impacts.

Moreover, there is a little variation in the previous affirmation "The transport impacts increase with the distance" as this is not true for Siniscola plant. Its impacts are lower than the impacts of Guidonia and Settimelo in spite of the distance. The explication regards the type of transport. Siniscola is placed in the island of Sardinia so marine transport is required unlike the others. From the results it can be concluded that marine transport impacts are lower than road transport impacts as it is also concluded in (James J. Corbett et al, 2002).

The results obtained in the two comparisons have the same behaviour for both types of geometries. Differences between the materials phase are logically found for the complex geometry as it is bigger and a larger amount of materials is required. Regarding the laboratory phase, it is significant for the simple geometry and almost negligible for the complex geometry as in this case the process is optimized because a larger amount of materials is used for the same power. Because of this common behaviour it can be concluded that the complex geometry confirms all the simulations done for the simple geometry.

Regarding the laboratory phase, it is concluded that when a low amount of cement is used (simple geometry), energy plays an important role but not when using higher amounts (complex geometry). Nevertheless, a comparison between the energy used in Italy, Spain and the United States was done in order to check if such high values in laboratory phase were due to the italian electricity, concluding that they were not and in fact, United States energy is the one which impacts the most.

On the other hand, a completely different study has been made in order to confirm the results obtained for CEM II ALL produced in Trino. As it has been explained, data for the production of this cement is declined in the first case from EPD and in the second case from real primary data provided by Buzzi Unicem. Indeed, from the results all the previous simulations made with the EPD data were confirmed as the error obtained was very little, ranging from about 0.001% in metal depletion and being its maximum of about 18% in only one of the eighteen categories, natural land formation.

As a general conclusion, it can be stated that from all the scenarios considered to guarantee a compression resistance of cements of 42.5R in reinforced concrete structures the Portland cement which gives lower environmental impacts is CEM II ALL and the best plant to have lower transport impacts needs to be near the place where the mix design and installation is performed.

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