Life cycle assessment of reinforced concrete units

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Abstract. Nowadays reinforced concrete is the material mostly used in the sector of civil construction. Different studies about its behavior when using different types and amounts of materials have been carried out, but only few researches have investigated how these choices can affect the environmental impacts. The final aim of the present work is to use the Life Cycle Assessment (LCA) methodology to compare environmental performances by using different scenarios, as changing the plants where the cement is produced or changing the type of cement used, always guaranteeing the same resistance to compression. The analysis is performed using SimaPro 8.2 software adopting a cradle-to-gate perspective. The results obtained by the ReCiPe 2008 method comparing both different cements and different materials production plants showed that the most significant changes were reported for the categories of *Climate change*, *Ozone depletion*, *Terrestrial acidification*, *Photochemical oxidant formation* and *Metal depletion* and that the materials phase is the most impacting one if compared to transports or manufacturing phases. Among the considered cements, the most impacting was CEM I 42.5 R while the least one was a pozzolanic cement (CEM IV/A 42.5 R). When changing the plants and keeping constant the type of cement, the plant characterized by the highest transport impacts was Augusta. On the other hand, the one that had less transport impacts was Vernasca, which is the closer to Milano, where the reinforced concrete structures are produced. So it can be concluded that also the transport impacts can play a significant role when distance is long and road transportation is used.

Introduction

Building construction consumes large amount of energy and material resulting in high impacts on the environment which need to be minimized [1]. These impacts occur from initial on-site work through the construction period, the operational period, and to the final demolition, when a construction comes to the end of its life.

Nowadays reinforced concrete is the material mostly used in the sector of civil construction [2]. Different studies about its behavior when using different types and amounts of materials have been carried out [3-5], but only few researches have investigated how these choices can affect the environmental impacts.

Life Cycle Assessment (LCA) allows for determination of the environmental impacts at each stage of a construction life cycle, beginning at the point of raw materials extraction, and then through processing, manufacturing, fabrication, use, and disposal. Transportation of materials and products to each process step is also included.

Habert et al. [6] evaluated by LCA the Global Warming Potential of bridge rehabilitations based on different types of ultra-high performance fiber reinforced concrete comparing them to standard solutions based on reinforced concrete and waterproofing membranes. Tait et al. [7] obtained by LCA the overall environmental impact, with a particular focus on carbon dioxide (CO_2) emissions, of three concrete mix designs while other studies [8, 9] quantified environmental impacts associated with mixing compositions of concrete made of waste materials by using LCA.

So LCA allows the optimization of materials and energy in order to promote sustainable development and it is generally the methodology used to investigate the effects of different mix design or construction choices on the environmental impacts.

The final aim of the present work is to use the LCA methodology to compare environmental performances of reinforced concrete structures by using different scenarios, as changing the plants where the cement is produced or changing the type of cement used, always guaranteeing the same resistance to compression.

The impact assessment is carried out using ReCiPe 2008 method starting with the evaluation of the impacts related to the materials if compared to the other production phases. Then a comparison between the different cements produced in each plan is carried out and finally the distance of the cement supplier for each type of cement is varied to compare the different plants.

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.

LCA methodology

The LCA methodology observes and analyses a product over its entire life cycle aiming at evaluating its environmental impacts [10, 11].

The stages included in a LCA study are the following:

- Definition of the scope of the study according to the aspired goals;
- Quantification of inputs and outputs flows of materials, energy and emission for each step of the analyzed processes (Life Cycle Inventory, LCI);
- Life Cycle Impact Assessment, LCIA;
- Discussion and interpretation of results, and process iteration, if needed.

Goal and scope definition. The goal of the present study is to assess the environmental impacts of reinforced concrete structures by using different scenarios, as changing the plants where the cement is produced or changing the type of used cement, always guaranteeing the same resistance to compression, so that their lifetime can be supposed the same for all of them.

The different considered cements types are: CEM I 42.5 R, CEM II/A-LL 42.5 R, CEM IV/A 42.5 R and the different cements production plants are located in Vernasca, Trino, Robilante, Settimelo, Guidonia, Siniscola, Barletta and Augusta (all in Italy).

The analysis follows the methodology defined by ISO 14040 and 14044 and it is performed using SimaPro 8.2 software adopting a cradle-to-gate perspective.

Functional unit and system boundaries. In a LCA study, the functional unit (FU) is a measure of the analyzed product system and it is a reference to which all inputs and outputs are related. The FU adopted in the present analysis is one manufactured reinforced concrete structure, with the geometry shown in Fig.1.

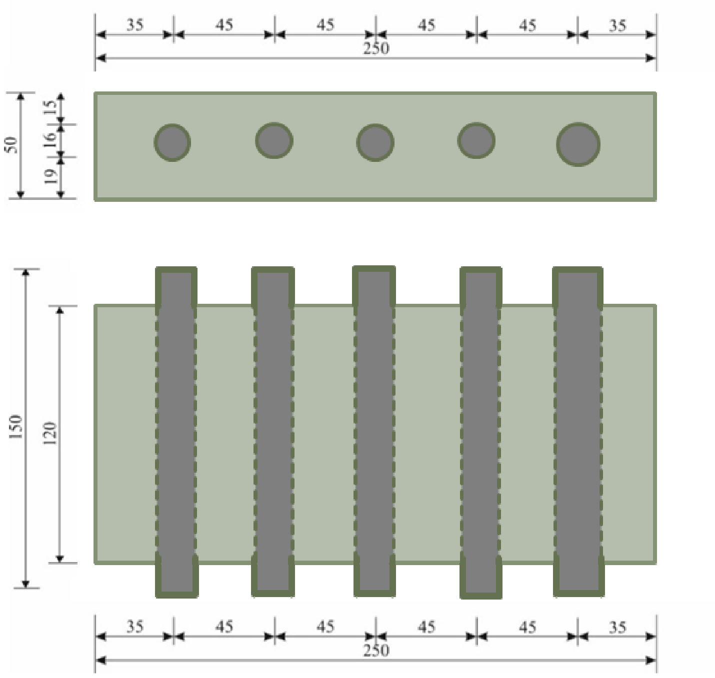

Fig. 1. Geometry of the manufactured reinforced concrete structure (measures in mm).

When manufacturing a reinforced concrete structure several processes are carried out, first the raw materials acquisition and their corresponding transportation, the mix design process, the structure realization, the installation, the maintenance and finally the repair, as it can be seen in Fig. 2. However, the approach adopted in this study is “cradle-to-gate”, i.e. from the raw materials acquisition to the manufacturing of the product.

The system boundaries and all the involved unit processes are showed in Fig 2. The so-called material phase comprehends the processes of material production; the transport phase considers the transportation from the production plants to the structure manufacturing phase; the manufacturing includes the mix design and the reinforced concrete structure realization. The process of energy production is accounted as input in all the phases. In the system boundaries, the downstream module [12] composed of installation, maintenance, operation, and repair is not considered.

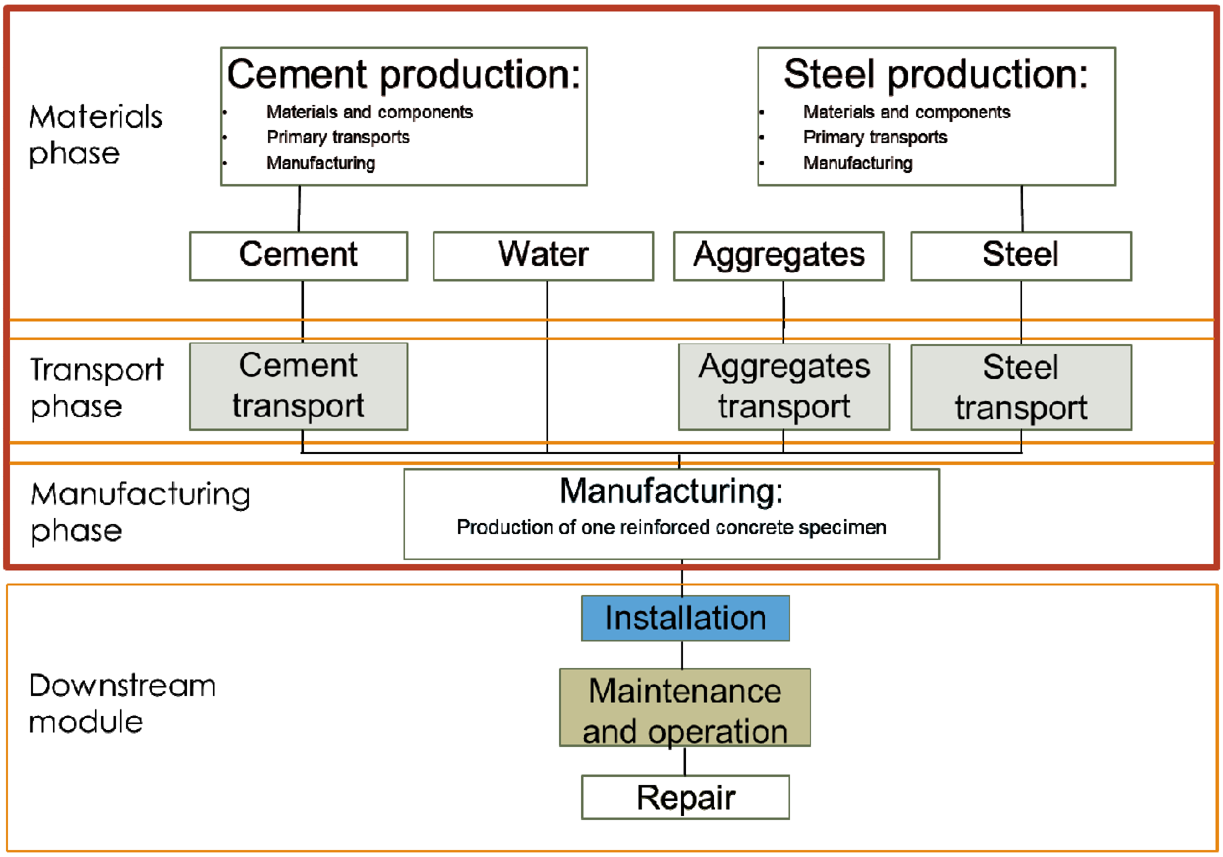

Fig. 2. Process scheme of a reinforced concrete structure. The system boundaries are highlighted in the red box.

Data and quality sources. In the present study, all the data regarding the manufacturing phase (as energy consumption of the mix design and energy consumption of the structure realization) are primary data obtained from the Concrete Laboratory at Politecnico di Milano. Other primary data are steel transport, cement transport, and aggregates transport to the Concrete Laboratory.

The secondary data used are: the mix design, derived from literature [13], and the cement type emissions, derived from the EPD (Environmental product declaration) provided by Buzzi Unicem.

The processes of energy generation, materials production and primary transports are taken from Ecoinvent 3.1 database. In detail, for electricity the Italian mix is selected, while European conditions are considered for transports and production of fuels.

Impact assessment method. Impact assessment is a fundamental step in LCA because it translates inventory data in potential environmental impacts. The impact assessment method selected in this work is the ReCiPe midpoint because it gives reliable data with low uncertainties, as confirmed in literature [14, 15]. The ReCiPe method includes the following categories: *Climate change*, *Ozone depletion*, *Terrestrial acidification*, *Freshwater eutrophication*, *Marine eutrophication*, *Human toxicity*, *Photochemical oxidant formation*, *Particulate matter formation*, *Terrestrial ecotoxicity*, *Freshwater ecotoxicity*, *Marine ecotoxicity*, *Ionizing radiation*, *Agricultural land occupation*, *Urban land occupation*, *Natural land transformation*, *Water depletion*, *Metal depletion*, and *Fossil depletion*.

Results and discussion

LCA of reinforced structure. The first investigated parameter is the effect of the different life stages in the production of reinforced concrete structures. The considered system boundaries include the materials phase, the transports of the materials to the manufacturing phase and the manufacturing phase. Simulations were carried out for all the different considered scenarios (different cements and cements production plants), even if in the following only the case of CEM I

42.5 R (Portland cement) and a plant which is not too far from the Concrete Laboratory at Politecnico di Milano (Robilante) is discussed. The obtained trend is reported in Fig. 3.

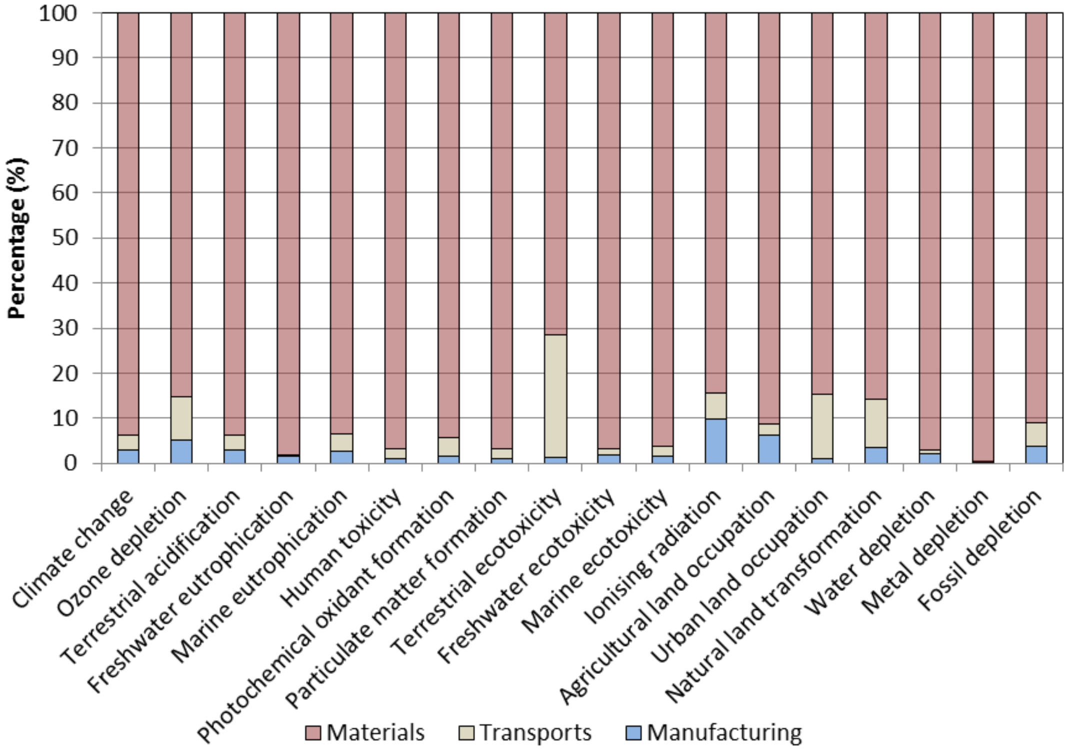

Fig. 3. Percentage impacts of the different considered life stages using CEM I 42.5 R produced in Robilante plant.

From Fig. 3 it results that the materials phase is the most impacting one (ranging from 71% to almost 100% in all categories), especially in *Metal depletion*, which takes the biggest value. The transport phase generally ranges from 0.2 to 14% resulting higher only in *Terrestrial ecotoxicity* with an average value of about 27%. The reasons of this behavior are mainly the brake wear and the tire wear emissions of the lorries The laboratory phase is indeed almost always negligible (from 0.05 to maximum 10%). Similar trends were obtained for all the combinations of cements and cements production plants, with the materials phase always characterized by the same highest impacts.

So the materials phase is found the most critical and, from the previous analysis, the use of different cements seems not to change the impacts in a relevant way. But to verify this behavior and to evaluate even the smallest environmental benefits, simulations were performed with the three different considered cements (CEM I 42.5 R, CEM II/A-LL 42.5 R, and CEM IV/A 42.5 R). CEM I 42.5 R is the Portland cement, CEM II/A-LL 42.5 R is Portland cement with high value of limestone and CEM IV/A 42.5 R is pozzolanic cement. Each of them is produced in different plants all around Italy and it is characterized by the same compression resistance; it means that their life phase can be supposed to be the same, so to compare them and their impacts. Simulations carried out in this way showed a common behavior for all the scenarios: 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. For this reason in Fig. 4 only the reductions in materials phase were reported. In particular, simulations were performed for all the production plants but in the following only the results obtained for Augusta plant are reported since in this plant all the three different considered cements are produced and a comparison results easier.

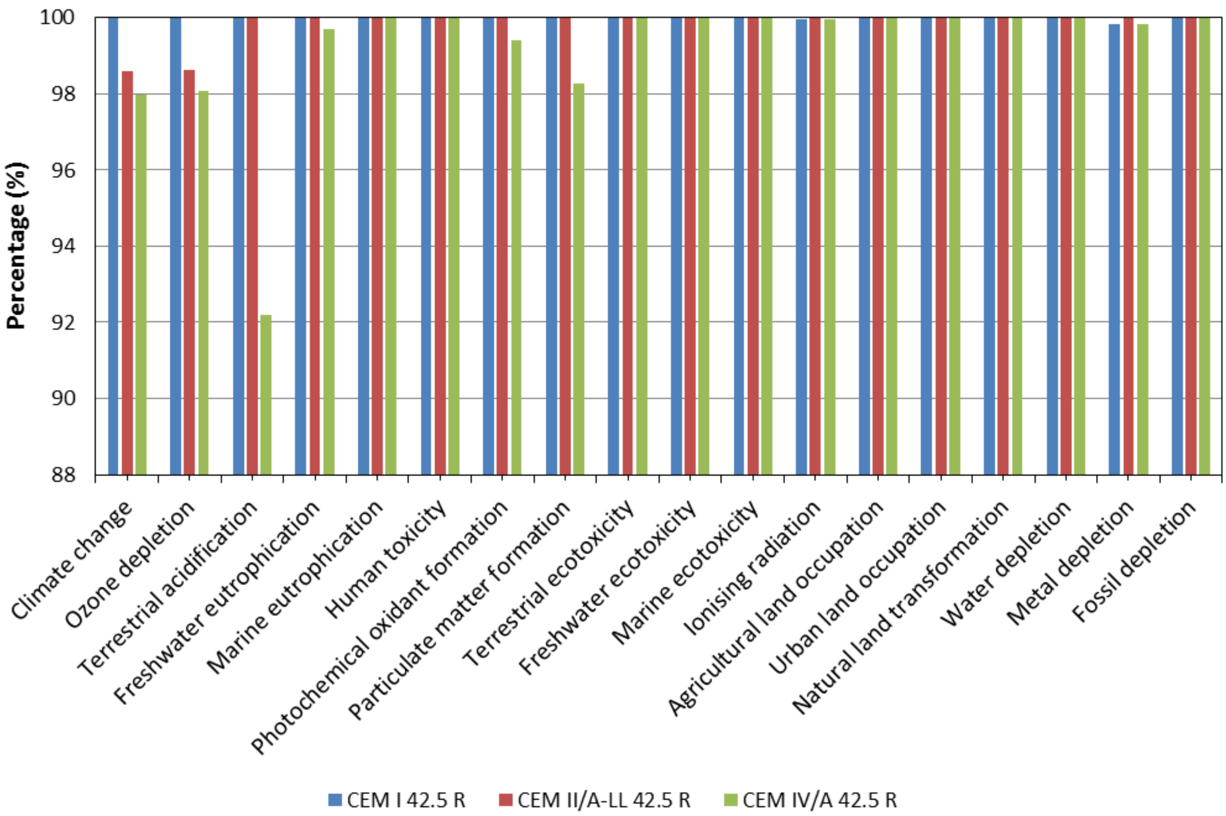

Fig. 4. Reduction values comparison of materials impacts in Augusta plant changing the cement type.

From the chart in Fig. 4 it is evident that CEM IV/A 42.5 R minimizes the environmental impacts in almost all categories, in particular in *Terrestrial acidification* (- 8% if compared to both CEM I 42.5 R and CEM II/A-LL 42.5 R). Also between CEM I 42.5 R and CEM II/A-LL 42.5 R there are differences: CEM II/A-LL 42.5 R reduces the impacts if compared with CEM I 42.5 R in *Climate change* and *Ozone depletion* (reduction value of about 2%). So, these results obtained comparing the different cements show that, among the considered cements, the most impacting is CEM I 42.5 R while the least one is a pozzolanic cement (CEM IV/A 42.5 R), confirming literature data [7-9]. The manufacture of Portland cement is proved to consume a great deal of energy resulting in high embodied energy and carbon dioxide emissions from clinker calcination, becoming less energy intensive by utilizing higher levels of pozzolanic materials such as fly ash [16].

The last studied variable is the effect of the cements production plant on the environmental impacts. In this case the significant changes are revealed only in the transports phase because the plants and of course the kilometers to the Concrete Laboratory are changed. For this reason in Fig. 5 only the impacts on the transport phase are considered. Furthermore, even if the simulations were performed on all the three cement types, only the ones related to CEM II/A-LL 42.5 are reported, simply because this kind of cement is produced in all the considered production plants, making possible the comparison.

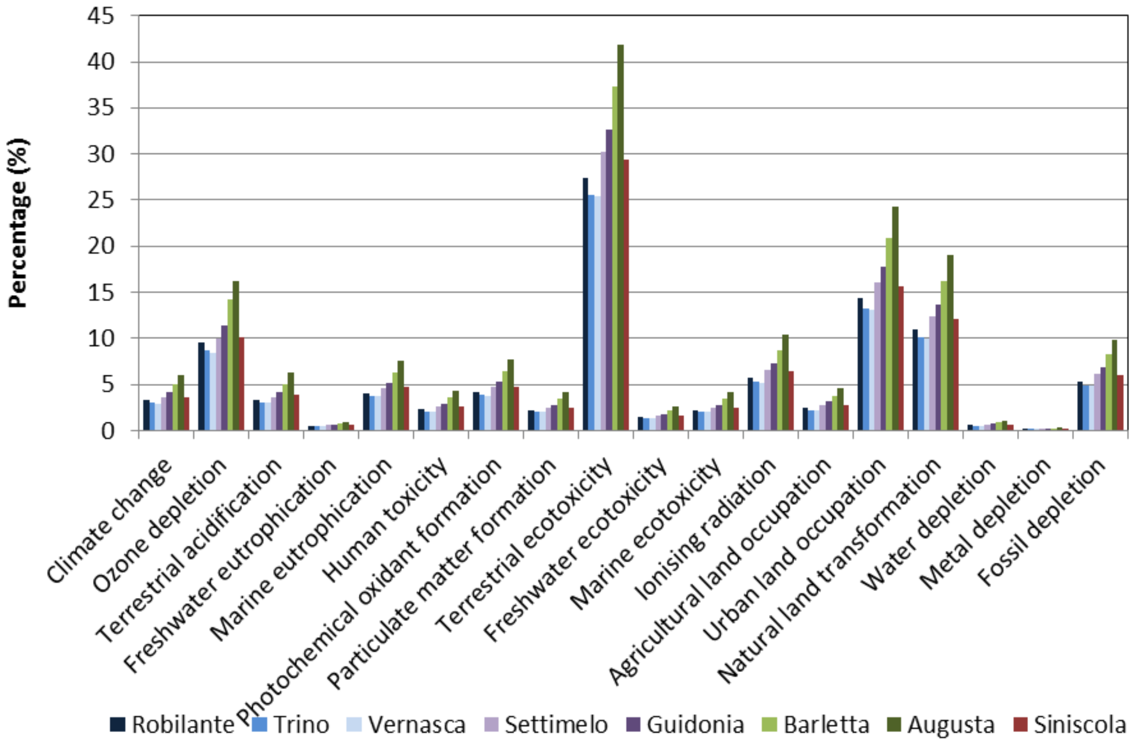

Fig. 5. Transport impacts for CEM II/A-LL 42.5 produced in the different plants.

From Fig. 5 it results that Augusta is the plant which gives more transport impacts (near 40% in *Terrestrial ecotoxicity*). This is reasonable as it is the furthest one from the Concrete Laboratory when travelling by road. So, at first sight the impacts increase with the distance.

In the case of Augusta plant, a normalization step was also carried out (Fig. 6) 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 was 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*. In Fig. 6 two charts reporting the transport impacts reductions as a function of the distance for both *Marine ecotoxicity* and *Freshwater ecotoxicity* are reported. In this way it is possible to highlight which plant reduces the impacts in the two found most relevant categories.

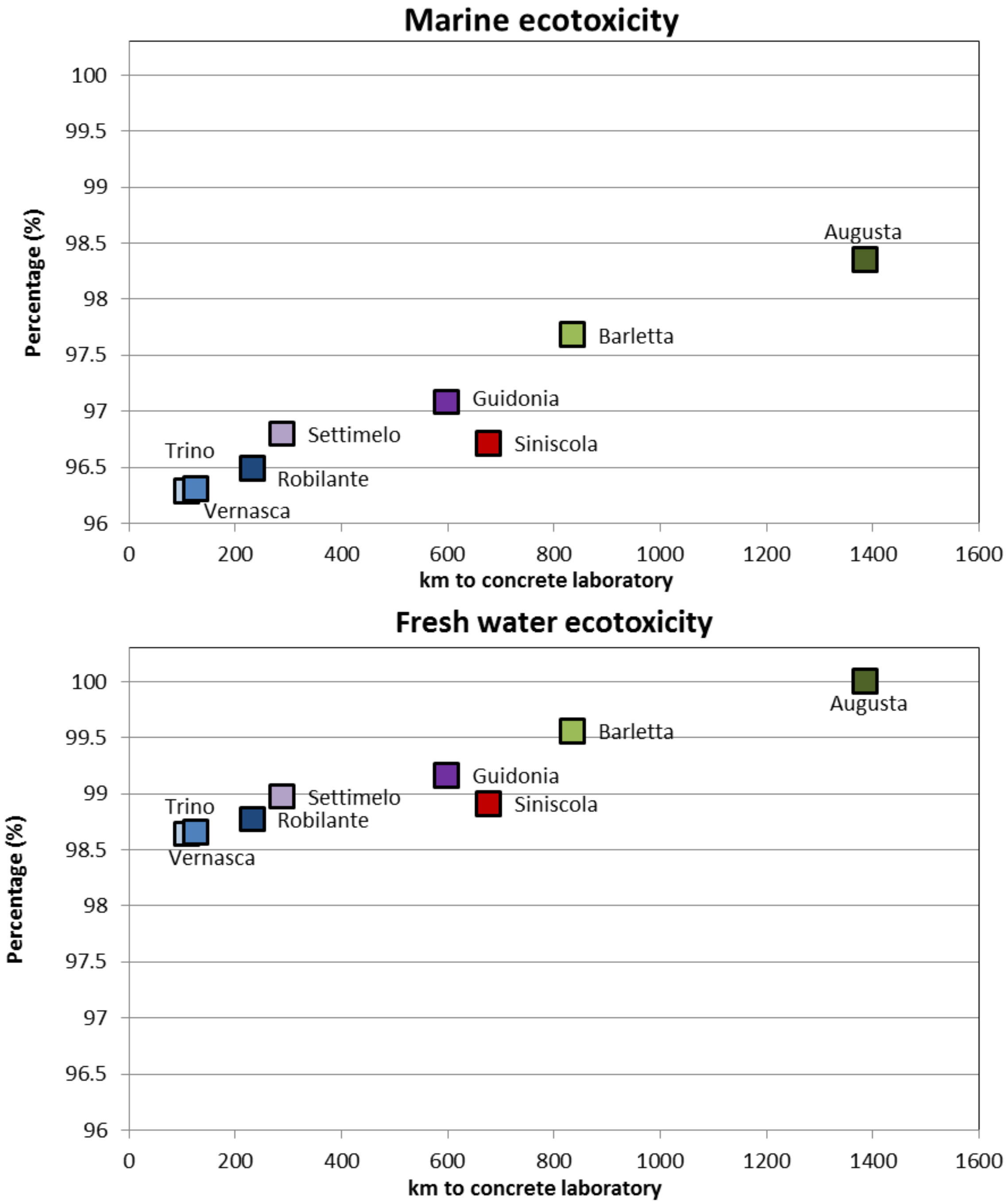

Fig. 6. Influence of production plant on the most impacting categories for CEM II/A-LL 42.5 produced in the different plants.

From Fig. 6 it is confirmed that Augusta plant is the most impacting one, while Trino and Vernasca are the less impacting plants. A linear trend is generally found, meaning that 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. Siniscola is indeed placed in an island and a ferry is needed: these results show that travelling by sea has fewer impacts than travelling by road.

Validation. Data of cements production were derived from the EPD (Environmental Product Declaration) provided by Buzzi Unicem. So, data of emissions to water and to soil were used to develop the simulations. In order to evaluate the accuracy of these calculations, a validation procedure was carried out. In particular, for a specific type of cement (CEM II/A-LL 42.5 produced in Trino plant) real primary data about production were provided by Buzzi. So, in this case, the simulations are not performed based on the emissions, but on real primary data of materials, energy and transport needed for the production of CEM II/A-LL 42.5 in Trino plant.

First of all, it results that the transport and the manufacturing phases do not change. This is not surprising because the cement production is the only variable considered in this validation procedure, reflecting in changes only in materials phase. For this reason the impacts were evaluated in the specific materials phase and the comparison between the environmental impacts of materials phase obtained from both the sources (EPD and primary data) is showed in Fig. 7.

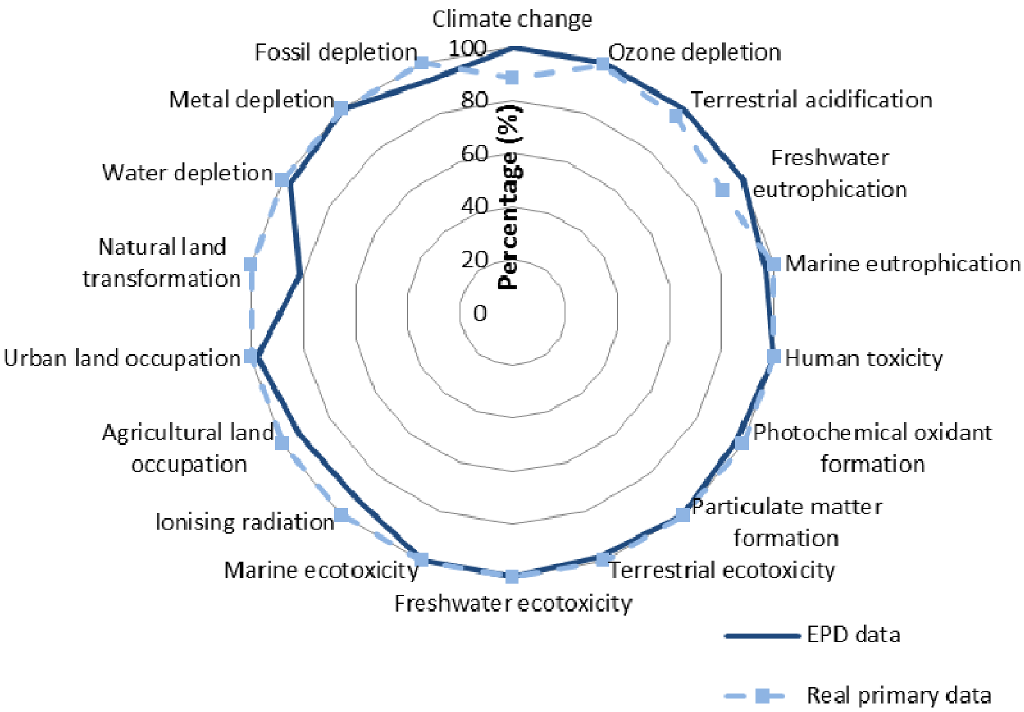

Fig. 7. Variation in materials impacts using EPD or real primary data for CEM II/A-LL 42.5 produced in Trino plant.

From Fig. 7 it can be concluded that the variations between the use of EPD data and real primary data are not significant: there is a certain error which depends on the categories and ranges from 0.001% in the case of *Metal depletion* to 18% only in the case of *Natural land transformation*.

So, although the different sources, data provided from EPD and real primary data present very small differences.

Conclusions and future work

The aim of this study was to evaluate the environmental impacts of reinforced concrete structures using several cements with the same compression resistance produced in different plants of Italy.

The results obtained by the ReCiPe 2008 method comparing both different cements and different materials production plants show that the most significant changes are reported for the categories of *Climate change*, *Ozone depletion*, *Terrestrial acidification*, *Photochemical oxidant formation* and *Metal depletion* and that the materials phase is the most impacting one if compared to transports or manufacturing phases.

The results obtained comparing the different cements show that the materials phase is the phase which gives more significant differences. In addition, among the considered cements, the most impacting is CEM I 42.5 R while the least one is a pozzolanic cement (CEM IV/A 42.5 R), confirming literature data.

When changing the plants and keeping constant the type of cement, the plant characterized by the highest transport impacts is Augusta. On the other hand, the one having less transport impacts is Vernasca, which is the closer to Milano, where the reinforced concrete structures are produced. So it can be concluded that also the transport impacts can play a significant role when distance is long and road transportation is used.

At the end, the validation study confirms the simulations carried out with the EPD and the good agreement between EPD and primary data: the error between the use of primary and secondary data is also estimated and is 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 transformation*.

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

Finally it is worth remembering that the life cycle evaluation of reinforced concrete structures cannot exclude the service life. It is indeed possible that some options consume more energy at the materials and manufacturing phases, but can save it back during the very long service life by good performances. So, future work will involve the impacts assessment of the total life cycle - from cradle-to-grave - including maintenance, service life and end of life treatment. Unfortunately when performing a LCA study on reinforced concrete structures there is a lack of data for operational/maintenance and end-of-life activities [17] but some results can be obtained normalizing the environmental impacts of the structures per year of their service life. In this way it should be possible to add coherence to life cycle environmental performance interpretation and to simultaneously communicate concrete environmental, functional and quality aspects [18].

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