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Variability of environmental impact of ready-mix concrete: a case study for Brazil

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Abstract. Life Cycle Assessment is a powerful tool towards sustainable construction, but it often relies on average impact results, failing to identify the dispersion of environmental impact among construction product manufacturers. This work presents cradle-to-gate impact results for ready-mix concrete production, based on primary data provided by several plants in Brazil, and the associated variability among plants and in the upstream processes of cement and sand production. Four compressive strength classes are considered. Concrete, cement and aggregates inventories are modeled with Brazilian information and other upstream processes are based on ecoinvent. EN 15804 impact categories are assessed. The ranges between minimum and maximum impact values can be as large as 7.2 times the average impact result of the analyzed sample, which shows that the variability among manufacturers is high and decisions based on average impacts may be highly misleading. For some impact categories, the differences among concrete plants (mix design, cement type and operational conditions) represent the highest contribution for variability, while for others the dominant variation comes from upstream processes, especially clinker production. These results indicate a high potential for process improvement and that manufacturer selection based on environmental performance can be an effective strategy for sustainable construction.

1. Introduction

Concrete is the most consumed manufactured substance on the planet [1]. It is a vital construction material, but also a key driver of many environmental impacts in the construction sector, including global warming potential [1], fossil fuels depletion [2], mineral resources depletion [3], water consumption [4], among others. Since concrete cannot be substituted by other construction materials on a large scale, it is essential to improve its environmental performance, which requires assessment methods capable of measuring the environmental impacts of concrete production and tracking the results of these improvement initiatives [5].

Life Cycle Assessment (LCA) suits well this purpose, due to its quantitative and comprehensive approach [6]. Many LCA studies on concrete have been conducted [2,7], with Life Cycle Inventories (LCIs) and Environmental Product Declarations (EPDs) for concrete and concrete products published in databases [8–13]. Most studies only disclose average impact values and therefore do not consider the variability of impact results among concrete producers or among suppliers of its raw materials



[2,7] and “average EPDs” are even accepted by standards [14–16]. Moreover, these averages are not necessarily calculated based on a statistically representative sample of the population.

However, studies show that the variability among construction material producers should not be disregarded. For concrete, differences in CO₂ emissions for the same strength class can easily reach 100 kg CO₂/m³ [17] and be as high as 400 kg CO₂/m³ of concrete, which is larger than the magnitude of the average emissions [18]. Different cement types and binder intensity explain these variations [19]. Furthermore, LCA studies on cement production show high variability among manufacturers [20,21]. Sand and gravel production also vary considerably in energy consumption and corresponding environmental impacts [22]. By adding the variability of the concrete production and of its upstream processes, impact values can significantly deviate from the average. In this scenario, selecting the optimum concrete source bears significant mitigation potential.

The aim of this work is to present and discuss cradle-to-gate impact results for ready-mix concrete production in Brazil and the associated variability due to differences between concrete plants, as well as variations in upstream processes, based on primary industry data.

2. Method

This study covers four concrete strength classes (characteristic compressive strength of 25 MPa, 30 MPa, 35 MPa and 40 MPa), made with two Brazilian cement types according to ABNT NBR 11578 [23]¹: CP-II-E (with addition of 6% to 34% of ground granulated blast furnace slag and up to 10% limestone filler) and CP-II-F (with addition of 6% to 10% limestone filler), with a 100 mm slump value.

Data about the concrete production process were collected via questionnaires responded by the managers of 34 ready-mix concrete plants, located in 10 different states of Brazil (predominantly in the state of São Paulo), on a voluntary contribution, under a confidentiality agreement. Each plant provided information about concrete mix design; consumption of water for the mixing and other purposes (such as mixer truck cleaning), electricity and diesel for internal equipment (such as loaders; the fuel used for mixer trucks is not included); consumption of other process inputs (lubricating oil, steel parts and rubber parts for replacing worn industrial equipment parts) and total concrete production for the year of 2017. These flows were informed based on plant controls per month, in order to avoid mistakes in the calculation of unit flows, which were done by the authors of this study. Validation of data was carried out by comparing the resulting inventories to literature data and existing datasets, and clear outliers were excluded.

Except for mix design and diesel consumption, some flows have not been reported by all plants. Electricity consumption, for example, was informed by only 79% of the plants. In such cases, the average of the reported flows was adopted for the plants that did not provide data for it. Although required, origins of raw materials to assess their transportation distances to the concrete plant were not informed, so they were approximated by the average distance informed by Brazilian concrete block manufacturers from their respective aggregate suppliers [22]. Despite covering multiple plants and regions, the data that were collected correspond to less than 10% of the national ready-mix concrete production volume for these strength classes [24] and this sample probably represents an optimistic estimate of the environmental performance of ready-mix concrete in Brazil, since it is composed of plants that agreed to deliver their data.

This data collection was part of a broader initiative to develop life cycle inventories for construction products in Brazil. Therefore, it was also possible to model the production of some raw materials based on primary data from the Brazilian industry, namely cement, including the production of clinker and the granulation and grinding of blast furnace slag, sand and gravel. For cement, data were collected from six Brazilian manufacturers, which represent about 70% of the national production volume, with plants distributed over the Brazilian territory, which allowed to assess the dispersion of impact results among cement manufacturers and plants. For natural sand, extraction from

¹ Superseded version, valid at the time of the data collection.

open pit and from riverbed sources were inventoried; however, each process was modelled using data from only one quarry, located in the South and Southeastern regions of Brazil. It was not possible to obtain variability information for gravel, since it was modeled using data from only one Brazilian manufacturer and one quarry.

Other upstream processes, such as the production of admixtures, provision of water, production of diesel, electricity and auxiliary inputs (lubricating oil, steel and rubber parts), were modeled using the ecoinvent database version 3.4, with the allocation system “cut-off by classification” and the geographical scope “Rest of the World” – except for electricity, since the Brazilian electrical mix is available in this database. The use of this database to provide part of the inventories, due to the lack of local data, has the drawback of underestimating the actual variation between companies, as discussed later. The variability of upstream processes modeled with the ecoinvent database was not taken into account, because uncertainty information cannot be considered representative for Brazil.

Cradle-to-gate life cycle impact assessment (LCIA) was carried out using the “CML baseline” method, considering the impact categories requested by EN 15804 [15]: abiotic depletion potential of elements (ADP-e), abiotic depletion potential of fossil fuels (ADP-f), global warming potential (GWP), ozone layer depletion potential (ODP), photochemical oxidation potential (POCP), acidification potential (AP) and eutrophication potential (EP); using the Simapro software version 8.5, excluding infrastructure processes.

Impact results were calculated for each mix design to assess the variability among concrete producers within a specific strength class, irrespective of the cement type, since in Brazil ready-mix concrete is usually requested by the strength class specified in the structural design and the cement type is chosen by the concrete producer (e.g. based on local availability). In this first step, upstream processes were modeled considering only their average values. Average, minimum and maximum concrete impact results were calculated from the sample, for each strength class.

A second step was carried out, considering the minimum and the maximum values of the embodied impact of cement (dispersion among manufacturers) and sand (variation between two production routes), in order to assess the effect of upstream variability on the variability of concrete impact results. Overall minimum and maximum concrete impact results for each strength class were extracted from this second step of analysis. Variability propagation was done using a simplified approach, in which ranges were compiled by combining all minimum and all maximum values for the impact results [25]. This approach assumes that all cement and sand manufacturers may supply all concrete plants with equal probability, which is a rather conservative estimate.

3. Results

Table 1 shows an overview of the average impact results for 1 m³ of ready-mix concrete, by strength class. Figure 1 shows the ranges between minimum and maximum impact values, expressed as relative numbers to the average impact (which is considered equal to 1.0), including the range only among ready-mix concrete plants (hatched bars) and the range considering upstream variability (grey bars). Table 2 shows the variations in concrete mix, with the minimum and maximum content of each material considering the sample of concrete plants, by strength class; no distinction was made between cement types because the ranges of material contents of both cement types overlap.

Table 1. Sample average impact results for 1 m³ of ready-mix concrete, by strength class.

Impact category	25 MPa	30 MPa	35 MPa	40 MPa
GWP (kg CO ₂ eq.)	196	220	248	295
ODP (10 ⁻⁶ kg CFC-11 eq.)	7.3	7.8	8.4	9.2
POCP (kg C ₂ H ₄ eq.)	0.031	0.034	0.038	0.044
AP (kg SO ₂ eq.)	0.74	0.80	0.87	0.98
EP (kg PO ₄ ³⁻ eq.)	0.14	0.15	0.16	0.17
ADP-e (10 ⁻⁵ kg Sb eq.)	1.3	1.3	1.4	1.5
ADP-f (MJ eq.)	707	761	825	911

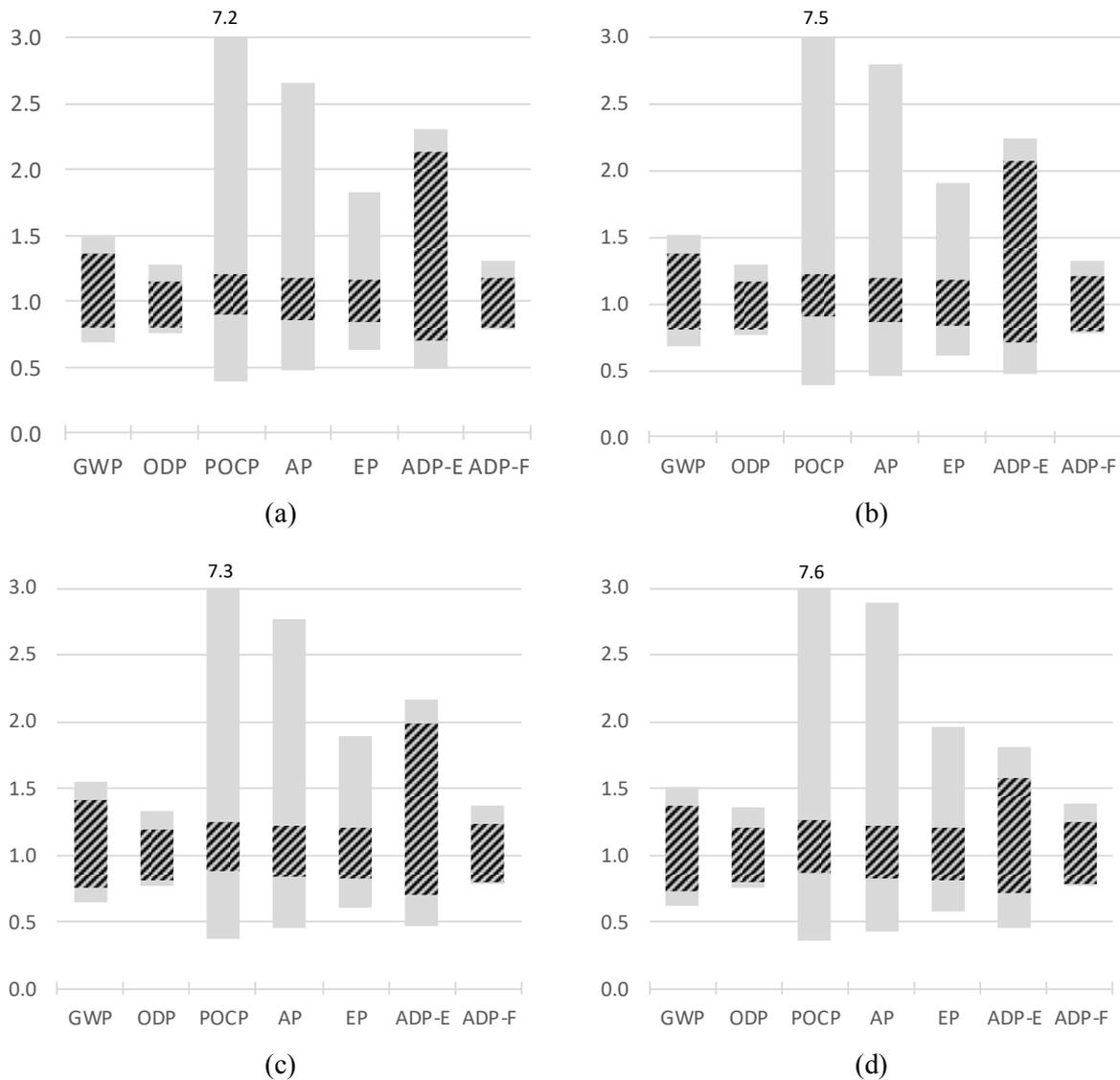


Figure 1. Impact result ranges relative to the average = 1.0; hatched bars: variation caused by differences among concrete plants; grey bars: variation caused by differences among concrete plants plus upstream variation (a) 25 MPa; (b) 30 MPa; (c) 35 MPa; (d) 40 MPa.

Table 2. Minimum and maximum content of materials in 1 m³ ready-mix concrete, by strength class.

Material	25 MPa		30 MPa		35 MPa		40 MPa	
	min.	max.	min.	max.	min.	max.	min.	max.
Cement (kg/m ³)	216	304	251	350	268	408	307	476
Natural sand (kg/m ³)	268	859	260	833	252	804	251	772
Artificial sand (kg/m ³) ^a	0	651	0	633	0	613	0	540
Gravel (kg/m ³)	1004	1193	1008	1201	1008	1176	1008	1232
Water (mix) (kg/m ³)	167	209	167	209	170	209	165	209
Admixture (kg/m ³) ^b	1.2	2.6	1.4	3.0	1.6	3.5	1.9	4.0

^a Very finely ground gravel, inventory modelled as gravel.

^b Plasticizer and polyfunctional admixtures.

Global warming (GWP) shows a considerable variation among ready-mix concrete plants, with minimum impact values up to 28% lower than the average and maximum impact values up to 41% higher than the average. The use of two different cement types, with different clinker content, along with variations in mix design (cement content) among producers (Table 2) explain the differences in the impact results. This variation corresponds to an impact range between 157 and 267 kg CO₂ eq./m³ for the 25 MPa strength class, i.e., a difference of 110 kg CO₂ eq./m³. This difference increases for higher strength classes, reaching 192 kg CO₂ eq./m³ for 40 MPa (between 213 and 405 kg CO₂ eq./m³).

For the impact categories ozone depletion (ODP), photochemical oxidation (POCP), acidification (AP), eutrophication (EP) and depletion of fossil resources (ADP-f), the ranges between minimum and maximum impact results are generally within the limits of $\pm 20\%$ relative to the average impact. These variations can be attributed mainly to differences in the mix design, especially cement consumption (which varies between -10% and +26% relative to the average consumption) and gravel consumption (which varies between -21% and +27% relative to the average consumption), since these inputs significantly influence these impact categories in concrete production.

The impact category with the highest variability among concrete plants is abiotic depletion of elements (ADP-e), with ranges from 0.70 to 2.14 times the average impact result, because this category has a significant contribution from the steel parts' consumption for factory maintenance and this flow cannot be estimated with a good accuracy level by manufacturers.

By considering the variations in upstream processes, the total variability of concrete impact results increases, but in different proportions according to the impact category. For GWP, ODP and ADP-F, the increase in the coefficient of variation is rather small. For GWP for example, there is an increase of up to 71 kg CO₂ eq./m³ between those limits compared to the fluctuation among ready-mix plants (for the 40 MPa strength class). Direct CO₂ emission from the clinker production process is the major cause for GWP and this flow shows low variability among cement manufacturers (coefficient of variation of 3%). Fossil fuel consumption is also similar among cement producers, which explains the low upstream variability for ODP and ADP-F. For ADP-e, the increase in the impact range is not significant and the variability among concrete plants is still predominant.

For POCP, AP and EP, the contribution of upstream processes to total variability is much larger than the variation among concrete plants. For EP, the range increases from approximately 0.4 times the average to 1.3 times the average. This increase can be attributed to variations in NO_x emissions among clinker manufacturers (coefficient of variation of 65%), since NO_x emissions cause 85% of clinker EP impact and the clinker contributes for 91% (CP-II-E) and 94% (CP-II-F) of cement EP impact (on average). Variations in NO_x emissions during clinker production are also a major variability source for AP (NO_x corresponds on average to 46% of clinker impact), together with variations in SO₂ emissions in the same process (coefficient of variation of 128% among manufacturers, contribution of 44% for the clinker impact result, contribution of clinker of 94% for CP-II-E and of 97% for CP-II-F impact results). Maximum values for the AP impact category can be almost 3 times higher than the average. The extremely high maximum impact values considering upstream variability observed for POCP (up to 7.6 times the average) occur because some cement manufacturers use charcoal as fuel for clinker production and the charcoal production process has a high POCP impact; if those manufacturers were excluded from the sample, the variability level would be similar to the AP impact category.

Impact results per cubic meter of concrete increase with the increase in strength, due to the corresponding increase in cement consumption. However, if the reference unit is changed from 1 m³ to 1 m³ x 1 MPa, by dividing impact results by the declared characteristic compressive strength (which defines the strength class), impact results generally decrease for the higher strength classes, as presented in Table 3. It can also be observed that the level of variation of impact results is similar for the different concrete strength classes. This reference unit (1 m³ x 1 MPa) is closer to the functional unit concept of LCA, since it includes the strength provided by the concrete [18].

Table 3. Sample average impact results for 1m³ x 1 MPa of ready-mix concrete, by strength class.

Impact category	25 MPa	30 MPa	35 MPa	40 MPa
GWP (kg CO ₂ eq.)	7.9	7.3	7.1	7.4
ODP (10 ⁻⁷ kg CFC-11 eq.)	2.9	2.6	2.4	2.3
POCP (10 ⁻³ kg C ₂ H ₄ eq.)	1.2	1.1	1.1	1.1
AP (kg SO ₂ eq.)	0.029	0.027	0.025	0.025
EP (10 ⁻³ kg PO ₄ ³⁻ eq.)	5.4	4.9	4.5	4.4
ADP-e (10 ⁻⁷ kg Sb eq.)	5.1	4.4	4.0	3.7
ADP-f (MJ eq.)	28	25	24	23

4. Discussion

Absolute differences between best and worst producers are staggering. Even for impact categories with lower levels of variation, maximum impact values (worst environmental performance) can be up to 1.5 times higher than minimum impact values (best environmental performance), exclusively due to differences in mix design and operation variables of concrete plants. For GWP, the indicator that is recognized as a priority for cementitious products, the difference between minimum and maximum values can reach values from 110 to 192 kg CO₂ eq./m³, which correspond to approximately 60% of the average impact values. These ranges are comparable to the dispersion assessed by Damineli et al. [18] and by Park et al. [17] for cradle-to-gate CO₂ emissions for concrete. They are also of the same magnitude of the ranges assessed by Oliveira et al. [22] for cradle-to-gate CO₂ emissions among concrete block producers in Brazil.

The results demonstrate the large mitigation potential of selecting the best ready-mix concrete producers. Although the technology adopted by ready-mix concrete producers is quite similar (dry batching trucks), there is large room for process improvements aiming to minimize the environmental impact of ready-mix concrete, such as optimization of mix design. Even though it might not be possible for all manufacturers to reach minimum impact values (for instance, due to local aggregates' characteristics), it is likely that some reduction can be achieved with existing technology and management measures.

Another important aspect is the propagation of variability of upstream processes to final variability. This study considered only the variations for the production of cement and sand, for which primary data were available, although for sand variation reflects only the differences between two production routes. The contribution of the variability of cement impact to the variability of concrete impact is relevant, especially for those impact categories affected by NO_x and SO₂ emissions, for which high variation has also been reported in literature about cement production [7,20,26]. Because sand contributes with a maximum of 9% to the total impact of concrete, the variation between production routes did not have a significant effect on the variability of concrete impact results.

Gravel constitutes most of concrete's mass and contributes with up to 66% of concrete's impact results. If variability in gravel production had been considered [22], total upstream variability would be certainly higher, as well as the variations in transportation distances for the raw materials to the concrete plants. Despite the underestimation caused by lack of data for upstream processes, the contribution of upstream variability to the total variability detected is still significant. These findings regarding upstream processes offer an additional evidence of the potential of mitigation given by the selection of suppliers of construction products.

Furthermore, these results show that decisions based on "average" or "typical" impact values can be highly misleading. Nevertheless, assuming that these single values are representative of a technology is, unfortunately, a common practice in LCA [2]. In our case study, the minimum error of using average values can be of 10% (disregarding upstream variability) or 21% (considering upstream variability), while in the worst case, these deviations can reach values up to 114% (no upstream variability) and 658% (with upstream variability). For GWP, for instance, the difference in impact results considering upstream variability ranges from 158 to 263 kg CO₂ eq./m³ (the higher being 1.7 times the lower) which is a considerable level since it is almost of the same magnitude of the average

impact. The variations observed are significantly above the level of variation recommended by ISO 21930 [14] for considering an “average EPD” valid, which is of $\pm 10\%$ of the environmental impact indicators, raising questions about the usability of those average assessments. By comparing technology options without considering variability between producers, one may select a product that looks better according to “average” values, but end up buying from a local producer that is actually much worse than its alternative.

Regarding uncertainty propagation, this work adopted a simplified approach of compiling ranges of extreme values, while there are more sophisticated techniques, e.g., Monte Carlo sampling. Although the probability of occurrence of extreme values is low (e.g., maximum cement content combined with maximum clinker content in cement and maximum emissions in clinker manufacturing), it is still possible since data were provided by existing suppliers. Therefore, the ranges presented here reflect the possible variations in ready-mix concrete impact results.

5. Conclusion

This work shows the high level of variation of life cycle impact results among some ready-mix concrete producers in Brazil, including both variations among concrete plants due to differences in mix design and among raw material suppliers. For GWP, the indicator most assessed for cement-based products, maximum impact values can be more than 2 times higher than minimum impact values. Depending on the impact category, total variability can be dominated by differences between concrete plants or by differences in the upstream processes.

It may be concluded that supplier selection based on environmental performance is a key strategy for reducing the overall environmental impacts in the construction sector, since bad performers will be forced by market conditions to improve their indicators, while good performers would be rewarded for their lower impact results. For decisions made when construction material suppliers are not yet defined, such as in early-design stages, the impact ranges must be considered when comparing technological alternatives and generic life cycle inventory databases must allow users to do so. This would allow LCA to effectively work as a sustainability promotion tool in the construction sector.

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