# Methodological discussion and piloting of LCA-based environmental indicators for Brazilian building materials

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## Abstract

Brazilian studies on sustainability indicators for the construction sector are considerably variable in criteria and methodology and therefore are not necessarily replicable or allow result aggregation. Worldwide definition and calculation procedures of some indicators also vary substantially. Life cycle assessment (LCA) can scientifically support such calculations, but is still embryonic in the country. This paper proposes the use of life cycle-based indicators to assess ecoefficiency (embodied energy; embodied $CO_{2eq}$; blue water footprint, abiotic content) and VOC emissions of building materials, normalized per unit of built area ($m^2$). This discussion is detailed for cement and concrete. The paper also examines the effects that discrepancies between two carbon footprint accounting methods (embodied $CO_2$ versus $CO_{2eq}$) have on communication of environmental performance of selected materials. Data for production cycle modeling were collected from national literature or, when considered acceptable, adapted from SimaPro 7.3 built-in Ecoinvent database. For the studied low rise, low window-to-wall ratio, concrete-framed buildings – a core database comprised of 12 materials and components - cement, ceramic blocks, steel rebar, sawn timber planks, PVC tubes, plywood, PVC conduits, roof steel structure, roundwood, ceramic tiles, hydrated lime and adhesive mortar - would provide a very reasonable description of a building's embodied energy (99.7%) and $CO_{2eq}$ (98.1%) profiles. Considering the general lack of LCA studies in Brazil, this could significantly streamline data collection work in the short term. Except for the blue water footprint, all calculated indicators captured the environmental advantages of partial replacement of clinker by ground granulated blast furnace slag (ggbs), a typical practice in Brazil. As granulation of ggbs is a well-known water intensive industrial process, most steelmaking companies have water reuse programs in place. To provide a general picture, such programs were not factored in the calculations shown here, but can be considered on a case-by-case basis. This research contributes to the construction of a Brazilian LCI open access database to enable application of the proposed LCA-based metrics to support design decision-making processes.

**Keywords:** indicators, LCA, carbon footprint, embodied energy, building sector.

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## 1. Introduction

The construction sector plays an increasingly important role on regional and global economies, contributing to jobs generation, to the development of new technologies and infrastructures and to quality of life enhancement. However, this social and economic relevance comes at a heavy environmental price: approximately 25% of all raw materials extracted from the lithosphere are consumed for building construction (BRIBRIÁN et al., 2011); about 23% of the energy produced in Brazil is consumed by the residential sector (ANEEL, 2008); and a great part of anthropogenic carbon emissions come from building activities.

Despite its environmental relevance, performance of a given construction project has traditionally been measured in terms of quality, time and money spent (GANGOLLELS et al., 2009). Environmental performance assessment is a relatively new practice and still presents methodological challenges that limit its practical application and accuracy. Silva (2007) points out that Brazilian studies aiming at defining sustainability indicators for the construction sector are considerably variable, with results obtained through criteria and methodologies that not necessarily are replicable or allow aggregation.

Variability within indicators' definition is observed worldwide, and calculations involved sometimes show clear conceptual conflicts, especially regarding accounting of carbon emissions. Wiedmann and Minx (2008) and ETAP (2007) defend that the carbon footprint should measure direct and indirect carbon dioxide emissions accumulated throughout a product's life cycle. On the other hand, Post (2006) states that the indicator should represent the total amount of all greenhouse gases emitted during a product or process' life cycle. Such discrepancy between definitions reveals that the calculation methodology is still quite irregular, and that results from different authors may lead to mistaken conclusions.

A set of indicators should provide a measure of current performance, a clear statement as to what can be achieved in terms of future performance goals and a reference point for progress measurement along the way (JEFFERSON et al., 2007). In other words, environmental indicators are designed to collect, process and use information aiming at making better decisions, at driving smarter political choices, and at measuring progress (WILSON et al., 2007).

Environmental indicators are structured to capture resources usage in terms of production and consumption, and their consequent environmental impacts. Some indicators are shared by many industry sectors such as water consumption, energy consumption and $CO_2$ emission (UN ST/ESCAP/2561, 2009). In the particular case of the construction industry, building material usage is usually described in terms of regional, renewable, recycled or recyclable content. A less common - but far more relevant indicator - is the non-renewable content, which communicates the depletion intensity of abiotic resources, as demonstrated by Saade et al. (2012). In the current scenario, in which data regarding the operational phase of a building's lifecycle are, many times, inaccurate and subjective, consideration of volatile organic compounds (VOC) emissions during the manufacturing phase might be a possible alternative to connect materials usage to health-related aspects in overall sustainability performance assessment.

To assure reliability and thoroughness, indicators should provide an entire lifecycle perspective. Life Cycle Assessment (LCA) stands out as a holistic tool to assess the potential environmental impacts throughout a product's lifecycle (ISO, 2006). The wide and comprehensive scope of LCA is useful in order to avoid "problem shifting" from one phase of the life cycle to another, from one region to another, or from one environmental problem to another (FINNVEDEN et al., 2009), and can scientifically support the calculation of more consistent and informative indicators.

This paper proposes the use of a set of life cycle-based indicators to assess ecoefficiency (embodied energy; embodied $CO_{2eq}$; blue water footprint, abiotic content) and VOC emissions of building materials, normalized per unit of built area ($m^2$), detailing the discussion for cement and concrete. It also analyses the effects that discrepancies between two carbon footprint accounting methods (embodied $CO_2$ versus $CO_{2eq}$) have on communication of environmental performance of selected materials.

# 2. Methodological approach

A literature review was carried out to cover the concept and applications of environmental indicators and LCA, particularly within the building industry, identifying the state of play and main barriers for their proper insertion in Brazil.

Based upon three case studies, the two main research targets were *(i)* to identify the building materials/components with the largest potential contribution to the building's embodied energy and $CO_2$; and *(ii)* to further calculate blue water footprint, abiotic (non-renewable) content, and VOC emissions, normalized per $m^2$, for the materials/components with the largest contributions, as found in item *i.* The performed cradle-to-gate LCAs followed ISO 14040 (ISO, 2006) methodological guidelines.

## 2.1 Quantification of materials and components mostly used in three case studies

Total usage of material/components was quantified for three low rise (up to 3 floors), low window-to-wall ratio (WWR), concrete-framed buildings. The case studies comprise one integrated service center (4,975.55 $m^2$); one police-training center (1,511.74 $m^2$); and one school building (4,869.23 $m^2$) and represent typical construction practices in Brazil for their respective functional categories. In the particular cases of concrete, steel rebar and formwork, only the superstructure was considered, in order to isolate the effects of soil's carrying capacity on the sizing – and, consequently, on material consumption - of foundation elements. External and urbanization elements were also disregarded.

For all case studies, consumption of each material/component was totalized (according to the functional unit previously defined), divided by the total built area and corrected by

Brazilian estimates for construction waste (AGOPYAN et al., 1998). Chart 1 indicates functional units and data sources used for production process modeling.

| Construction materials and components | Functional unit | Data source |
|---|---|---|
| **Concrete (fck 30)[1]** | 1 cubic meter | Silva, 2006 |
| **Portland cement (CPI-32, CPII-E-32 e CPIII-32)[1]** | 1 ton | Silva, 2006 |
| **Steel rebar, steel frame, wire, copper wire** | 1 ton | ELCD, version 2.0 |
| **PVC (conduit and tube)** | 1 ton | Industry Data, version 2.0 |
| **Wood (plywood; planed dried; raw dried)** | 1 cubic meter | Ecoinvent, version 2.2 |
| **Sand, Gravel, Acrylic paint, Hydrated lime, Adhesive mortar, Ceramic tile** | 1 ton | Ecoinvent , version 2.2 |
| **Ceramic block** | 1 ton | Manfredini and Sattler (2005); Hammond and Jones (2006) |

[1] Concrete mixes using three types of cement with different amounts of ground granulated blast furnace slag (ggbs) as clinker replacement are presented to best represent the Brazilian practice.

***Chart 1 - Inventory data sources and functional unit defined for each material or component considered in the study***

## 2.2 Calculation of the embodied energy and carbon footprint

The embodied energy indicator (EE), normalized by the functional unit previously defined, was calculated using LCI provided by Ecoinvent. The exception was the ceramic block, which used data from Manfredini and Sattler (2005), whose adopted methodological approach was explicit and seemed reasonably close to the one herein adopted. EE calculation considered the total energy from all primary sources indicated in the inventory.

Two scenarios were contrasted: embodied $CO_2$ emissions only - as defined by the Kyoto Protocol - and embodied $CO_{2eq}$ emissions, which included all greenhouse gases (GHG). For the sake of efficiency and practicality, embodied $CO_{2eq}$ was obtained through *CML 2001 v.2.05* environmental impact analysis, regarding the global warming impact category. The method contains the equivalency factors for all GHGs, and already expresses results in Kg of $CO_{2eq}$ per functional unit.

Embodied $CO_2$ and embodied $CO_{2eq.}$ per functional unit were calculated from the inventory analysis for each material/component, again except for the ceramic block value, which was obtained from University of Bath's inventory of carbon and energy (HAMMOND; JONES, 2011). Though these authors used an energy mix that differs from the Brazilian case, and such a difference can imply in less accurate results, the methodological thoroughness observed in their research suggest its use as a potential proxy, given the lack of data related to that specific component in national and international LCI databases.

## 2.3 Calculation of the blue water footprint, abiotic (non-renewable) content and VOC emissions

Embodied energy and embodied $CO_{2eq}$ per built m² were the initial filters applied to select material/components for which the other metrics would be calculated. Blue water footprint (bWF), abiotic (non-renewable) content (NRc) and volatile organic compound emissions (VOCe) per functional unit were then calculated from the inventory analysis. For the blue water footprint calculation, consumption of different water sources during the extraction and production was totalized. Consumption of mineral resources throughout the product's life cycle fed the abiotic (non-renewable) content calculation, while the VOCe indicator summed both methane and non-methane VOC emissions listed in the inventory.

# 3. Results presentation and discussion

## 3.1 Embodied energy (EE) per unit of built area

Figure 1 presents median values of embodied energy of building materials and components per built m². To support discussions made later on this paper, embodied energy of Portland cement and concrete are expressed in terms of three amounts of ground granulated blast furnace slag (ggbs) used as a clinker replacement (CP I-S-32, with 5% ggbs; CP II-E-32, with 30% ggbs; and CP III-32, with 66% ggbs), consistent with Brazilian standards NBR 5732 (ABNT, 1991), NBR 11578 (ABNT, 1991) and NBR 5735 (ABNT, 1991). Portland cement here indicated was not used to manufacture concrete, which was delivered ready mixed, but instead acquired separately for use in other cement-based applications. Figure 1 highlights that – if considered as a composite material delivered to the construction site - concrete would bring in the second highest contribution to EE and its use must therefore be carefully monitored during design and construction.

In Figure 2, concrete was broken down into corresponding cement, sand and gravel quantities, which were added to those, used in other construction applications. Top ten contributors to EE per built $m^2$ would therefore be cement, ceramic block, steel rebar, sawn timber planks, PVC tubes, plywood, PVC conduits, roof steel structure, sawn roundwood and ceramic tiles. These materials cover 99.2% of the accounted EE value for the case studies median, and seem to provide a very reasonable description of a building's embodied energy profile.

As expected and documented in previous literature data, results show that Portland cement and concrete are the main contributors to the building's embodied energy profile. It is noteworthy, however, that international studies usually investigate performance of ordinary Portland cement (OPC). OPC is composed primarily by clinker, with little or no mineral admixtures and would be equivalent to Brazilian cement type CP I-S-32. In Brazil, however, CP II-E-32 (30% of ggbs) is most widely commercially available type, while CP III-32 (66% of ggbs) is the top selling cement in the region of this study. Results for these cement types were therefore presented for reference purposes and to support discussion presented later in this paper.

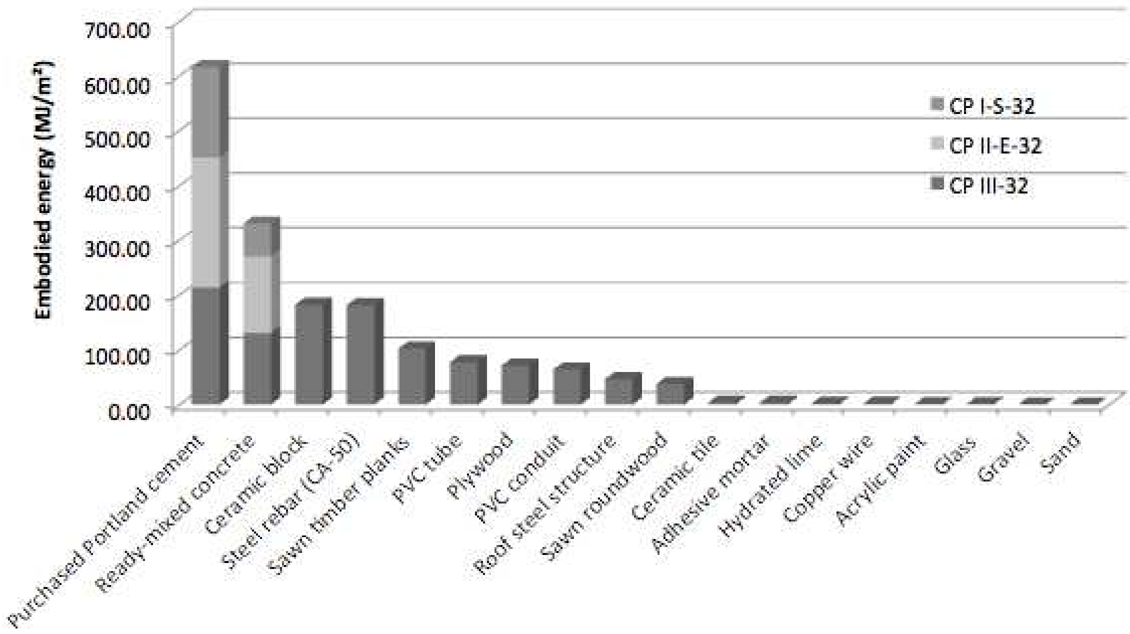


***Figure 1 - Embodied energy of materials and components normalized per m$^2$ of built area***

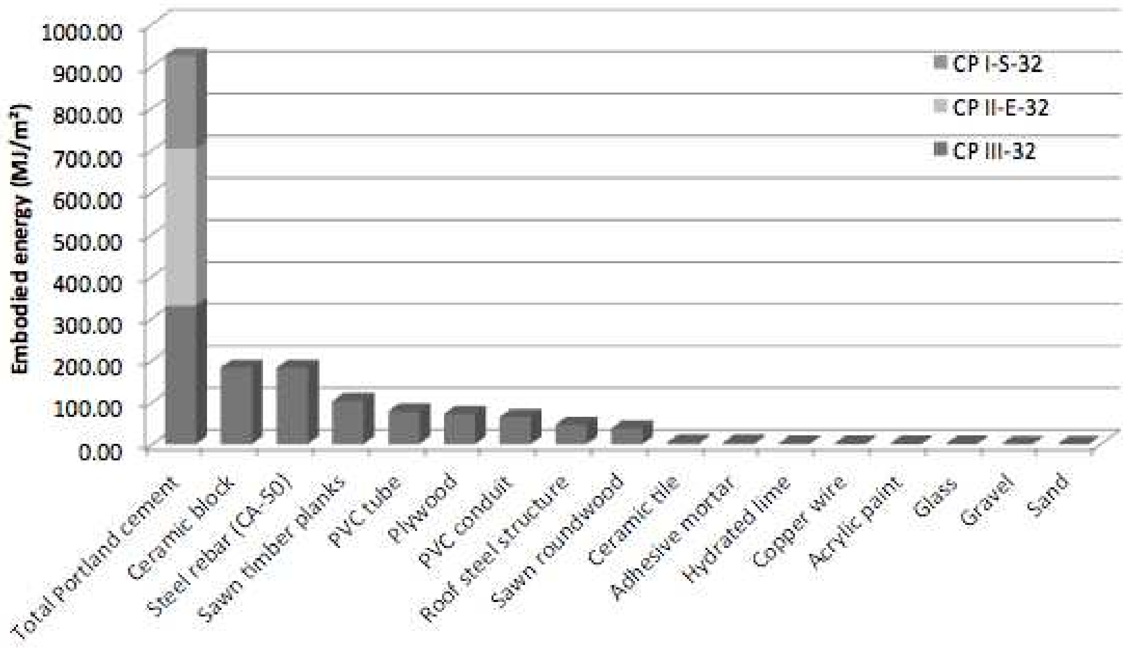


***Figure 2 - Embodied energy of materials and components normalized per m$^2$ of built area, with concrete broken down into corresponding cement, sand and gravel quantities***

### 3.2 Embodied $CO_2$ (EC) emission and embodied $CO_{2eq}$ ($EC_{eq}$) per unit of built area

Figure 3 presents median values of embodied $CO_2$ of materials and components per $m^2$ of built area. Repeating the pattern obtained for EE, Figure 3 shows that, according with the type of cement used, concrete, taken as a composite, would be the second highest contributor to embodied $CO_2$.

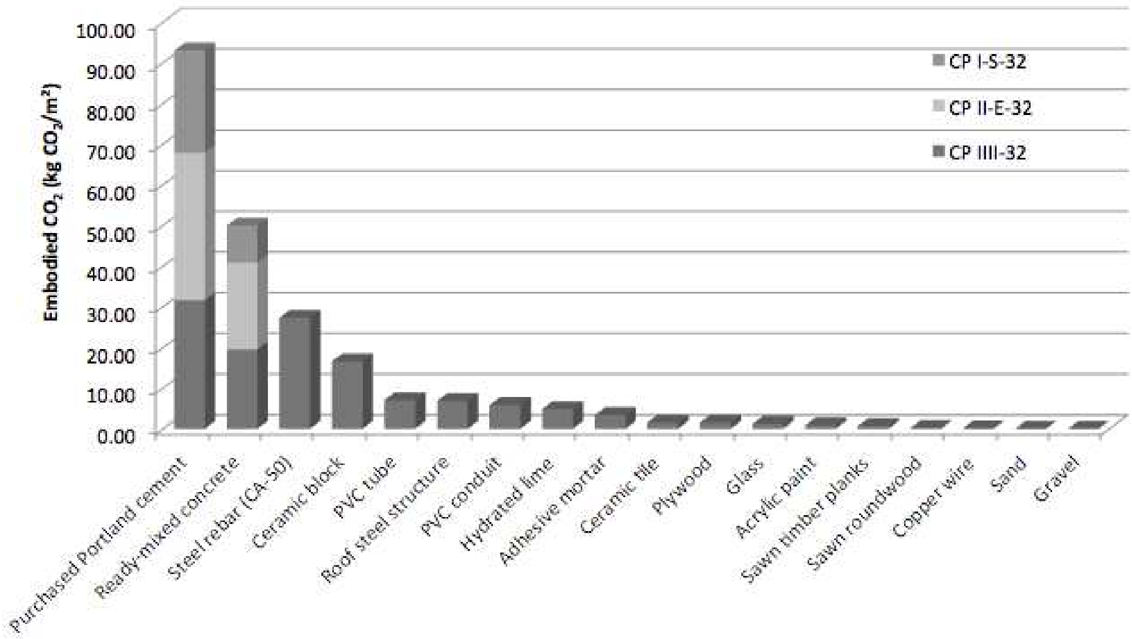


***Figure 3 - Embodied $CO_2$ of materials and components normalized per $m^2$ of built area***

Figure 4 presents median values with concrete broken down into corresponding cement, sand and gravel quantities, which were added to those, used in other construction applications. The top five contributions (cement, steel rebar, ceramic blocks, PVC tubes and roof steel structure) respond for 83.9% of the total embodied $CO_2$. Enlarging this collection to include PVC conduits, hydrated lime, adhesive mortar, ceramic tiles and plywood increases coverage to 97.4% of the accounted embodied $CO_2$.

Figure 5 presents the median values of embodied $CO_{2eq}$ for all quantified materials considering concrete as a composite material, while in Figure 6 concrete was broken down into corresponding cement, sand and gravel quantities, which were added to those used in other construction applications.

Apart from some reordering, the top 10 contributors for embodied $CO_{2eq}$ were the same as for embodied $CO_2$: cement, steel rebar, ceramic blocks, PVC tubes and PVC conduits respond for 82.8% of the total embodied $CO_{2eq}$, while consideration of the top 10 contributors (roof steel structure, hydrated lime, adhesive mortar, plywood and ceramic tiles) increases coverage to 97.4% of the accounted embodied $CO_{2eq}$. Most of these materials or components were also among the major contributors to EE.

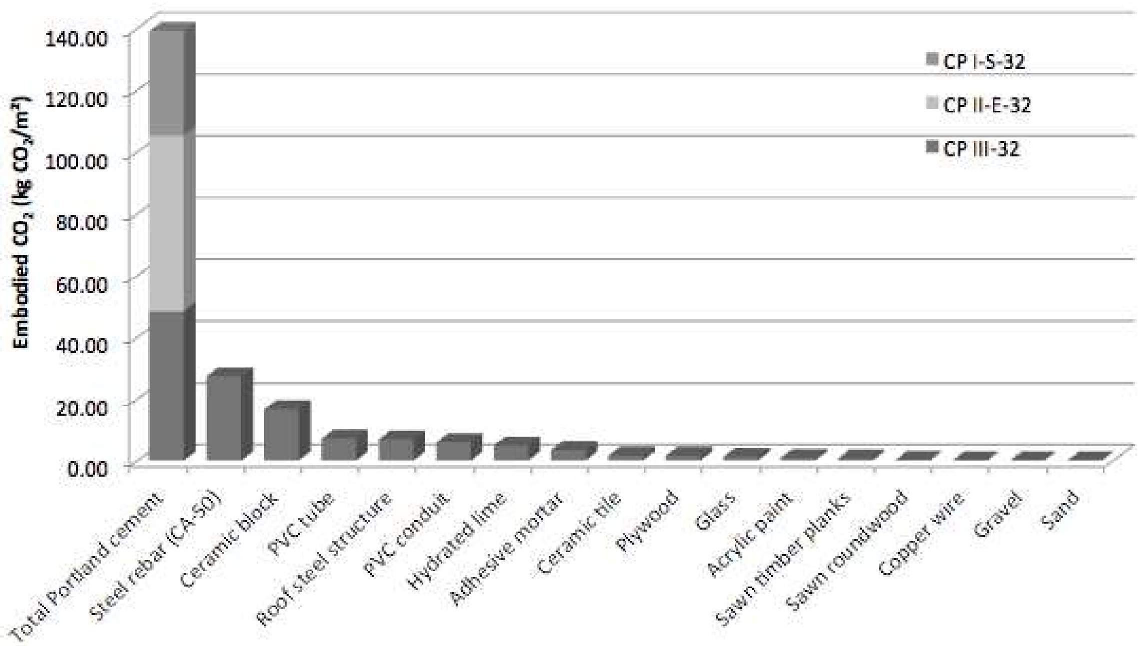


***Figure 4 – Embodied $CO_2$ of materials and components normalized per $m^2$ of built area, with concrete broken down into corresponding cement, sand and gravel quantities***

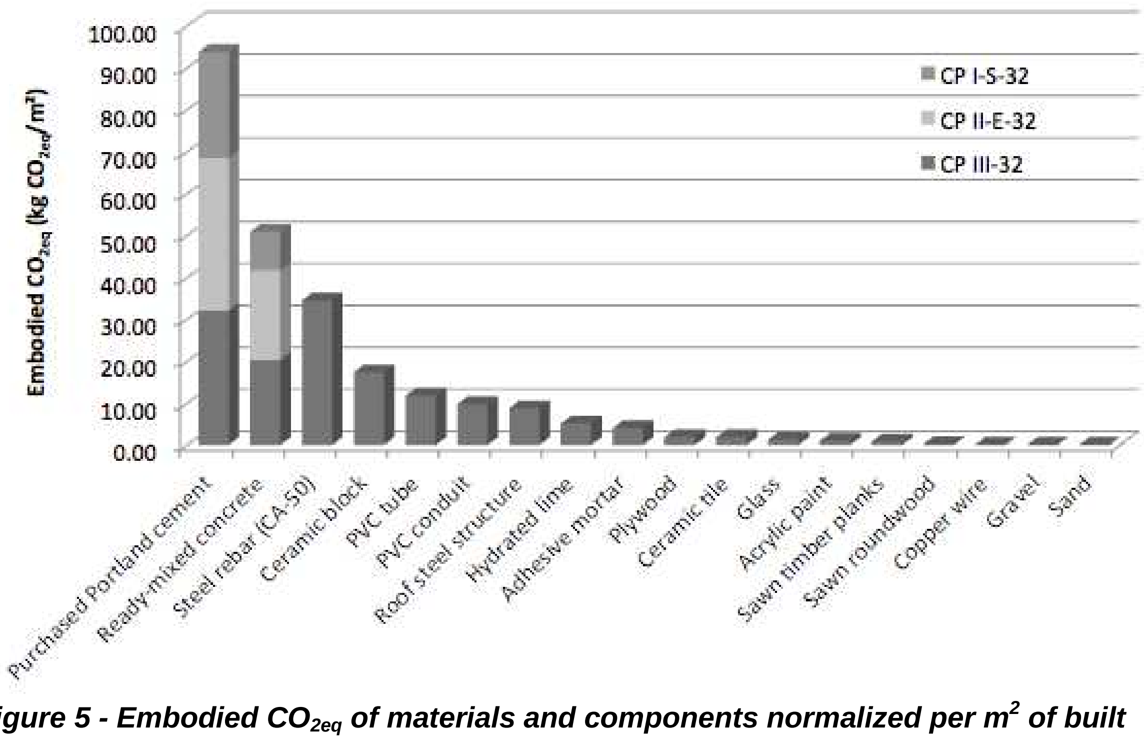


***Figure 5 - Embodied $CO_{2eq}$ of materials and components normalized per $m^2$ of built area***

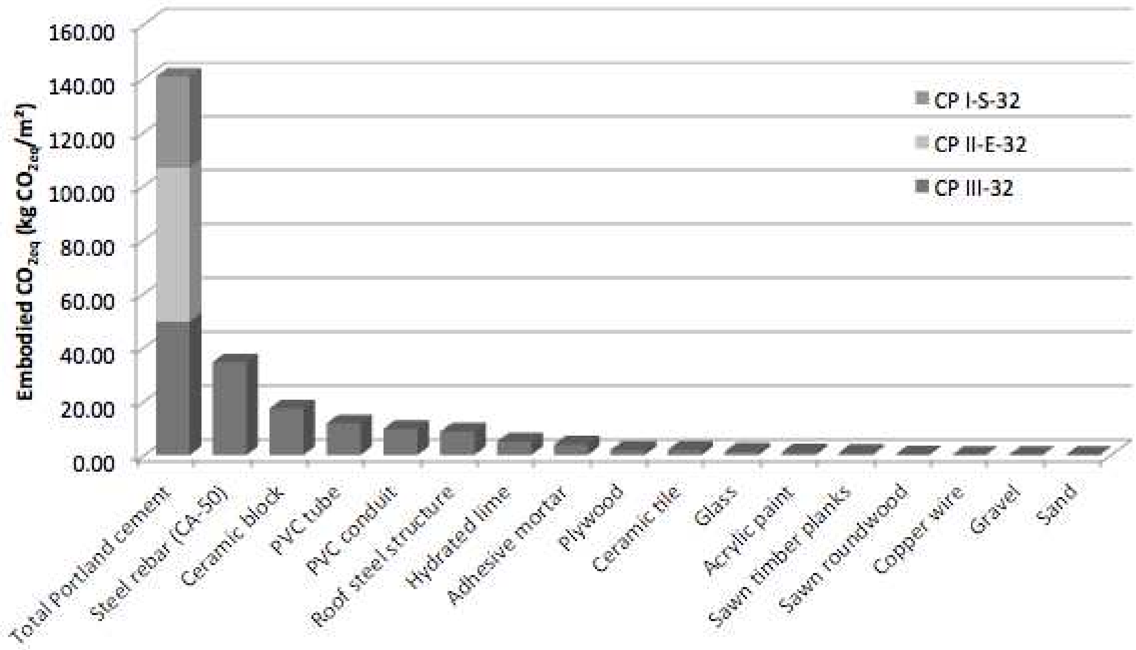


***Figure 6 – Embodied $CO_{2eq}$ of materials and components normalized per $m^2$ of built area, with concrete broken down into corresponding cement, sand and gravel quantities***

Combined analysis of accounted embodied energy and GHG emissions therefore suggests that a core database comprised of 12 materials - cement, ceramic blocks, steel rebar, sawn timber planks, PVC tubes, plywood, PVC conduits, roof steel structure, roundwood, ceramic tiles, hydrated lime and adhesive mortar - would provide a very reasonable description of a building's embodied energy (99.7%) and $CO_{2eq}$ (98.1%) profiles. Considering the general lack of LCA studies in Brazil, this could significantly streamline data collection work in the short term.

## 3.3 Discussion on proposed core set of environmental indicators

In order to advance in the evaluation of the most critical materials, values of embodied energy (EE), embodied $CO_2$ (EC), embodied $CO_{2eq}$. ($EC_{eq.}$), blue water footprint (bWF), abiotic (non-renewable) content (NRc) and Volatile Organic Compounds emissions (VOCe) normalized per unit of built area were calculated for cement and concrete (Table 1). Table 2 presents the normalized values found for concrete with cement types CP I-S-32, CP II-E-32 and CP III-32. Figures within parenthesis indicate reductions in relation to cement CP I-S-32 (the most similar to OPC), kept for international reference.

Except for the blue water footprint, all calculated indicators confirm the environmental advantages of using ggbs as clinker replacement in cement (Table 1) and concrete manufacturing (Table 2). The bWF value increased when shifting from CP I-S-32 to CP III-32 and corresponding concrete mixes, as granulation of blast furnace slag is a well-known water intensive industrial process. Most steelmaking companies have water reuse programs in place, which would reduce cement and concrete's blue water footprints. In this paper, however, such programs were not considered, because of the unpredictable differences across steelmaking companies' environmental management programs.

*Table 1 - Indicators calculated for cement types CP I-S-32, CP II-E-32 and CP III-32*

| | EE ($MJ/m^2$) | EC ($kgCO_{2eq}/m^2$) | $EC_{eq}$ ($kg/m^2$) | bWF ($m^3/m^2$) | NRc ($kg/m^2$) | VOCe ($kg/m^2$) |
|---|---|---|---|---|---|---|
| **CP I-S-32** | 924.00 | 139.37 | 140.54 | 0.12 | 470.59 | 4.85E-4 |
| **CP II-E-32** | 702.49 (-23.97%) | 105.57 (-24.25%) | 106.59 (-24.16%) | 0.70 (+82.26%) | 358.15 (-23.89%) | 4.21E-4 (-13.15%) |
| **CP III-32** | 329.79 (-64.31%) | 48.81 (-64.98%) | 49.53 (-64.76%) | 1.50 (+91.77%) | 168.88 (-64.11%) | 3.00E-4 (-38.13%) |

*Table 2 - Indicators calculated for concrete with cement types CP I-S-32, CP II-E-32 and CP III-32*

| | EE ($MJ/m^2$) | EC ($kgCO_{2eq}/m^2$) | $EC_{eq}$ ($kg/m^2$) | bWF ($m^3/m^2$) | NRc ($kg/m^2$) | VOCe ($kg/m^2$) |
|---|---|---|---|---|---|---|
| **Concrete w/ CP I-S-32** | 330.41 | 49.95 | 50.84 | 0.82 | 695.78 | 1.85E-3 |
| **Concrete w/ CP II-E-32** | 271.02 (-17.97%) | 40.85 (-18.22%) | 41.68 (-18.01%) | 1.00 (+18.36%) | 638.94 (-8.17%) | 1.74E-3 (-5.57%) |
| **Concrete w/ CP III-32** | 131.12 (-60.32%) | 19.55 (-60.85%) | 20.28 (-60.11%) | 1.30 (+37.10%) | 576.26 (-17.18%) | 1.72E-3 (-6.69%) |

## 4. Conclusions and final remarks

Many efforts to describe environmental performance, through establishment of adequate indicators, have been observed throughout the world. However, there are significant disagreements in terms of definitions and calculation methods. Such differences can mislead interpretation, especially when the calculation protocols are not explicit, increasing risk of cumulative errors. Another possible limitation arises from the deficiency of national and international reference for data input in LCA platforms, which might require input from mixed data sources, as in the case of this paper.

Obtained results showed that adoption of different methodologies for carbon accounting had little effect on the values calculated for cement ($EC/EC_e$ ratio between 98.5-99.2%) and concrete ($EC/EC_e$ ratio between 96.4-98.2%). This is not necessarily the case for all relevant building materials, as shown in Figure 3 versus Figure 4 and in Figure 5 versus Figure 6.

Contribution of cement to EE and $EC_{eq}$ per built $m^2$ increases almost threefold when shifting from Brazilian CP III-32 to CP I-S-32 (two and half times, in the case of concrete). CP I-S-32 is the closest type to the ordinary Portland cement (OPC) used internationally, and is a good example of the adhesion to local practice data needed to deliver meaningful analysis. Except for bWF - increased due to the water-consuming granulation process – all proposed indicators reflected the environmental advantages of ggbs as clinker replacement in cement production. This complements improvement of some technical properties consistently pointed out in literature (CAMARINI, 1995; SILVA, 1998; SILVA, 2006; TANESI, 2010).

Combined analysis of accounted embodied energy and GHG emissions therefore suggests that a core database comprised of 12 materials would provide a very reasonable description of a building's embodied energy and $CO_{2eq}$ profiles. This could significantly streamline work on Brazilian LCI assembly in the short term. Next research steps include investigation of additional material intensity/dematerialization indicator and database expansion to include other building typologies. Following a coordinated methodological outline, future works will gradually evolve to form an LCI open database comprising the most relevant building materials and components, to enable the use of the proposed LCA-based metrics to support design decision-making processes.

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