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ARTIGO

# METHODOLOGICAL DISCUSSION AND PILOTING OF LCA-BASED ENVIRONMENTAL INDICATORS FOR PRODUCT STAGE ASSESSMENT OF BRAZILIAN BUILDINGS

## Indicadores com Base em ACV para Avaliação Ambiental do Estágio de Produto de Edificações Brasileiras: Discussão Metodológica e Aplicação-piloto

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**ABSTRACT** The International Energy Agency (IEA)'s Annex 57 was established to advance on evaluation of embodied energy and GHG emissions for building construction. Its activities include recommendation of common calculation methods and disclosure of regional benchmarks. Process-based, input-output or hybrid life cycle assessment (LCA) can support such calculations. Identification of the major products that describe key building typologies plays a strategic role in the tasks of streamlining indicators' monitoring scope and LCI data gathering in contexts with little LCA practice consolidation. Given these motivations and backdrops, our main goals are (i) to calculate a selected set of LCA-based indicators to synthetically describe environmental performance of construction products for three functionally equivalent case studies; (ii) to detect the major contributors to embodied energy (EE) and emissions (EGWP); and (iii) to examine the implications of considering embodied $CO_2$ **versus** total GHG emissions. The selected metrics include – besides EE and EGWP targeted by Annex 57 – the blue water footprint (bWF), non-renewable primary material consumption (NRc) and volatile organic compounds (VOC) emissions. Production cycle modeling used previously collected national data, as well as secondary data extracted from national and international literature or adapted from international databases whenever considered as reasonably similar to Brazilian processes. EE and EGWP results were calculated using the Cumulative Energy Demand (CED) method and the CML 2001 baseline v. 2.05 method, respectively, and are presented for the top contributing products. NRc, bWF and VOC calculations were directly derived from the inventories and discussed in more detail for cement and concrete. Around 80% of the total embodied energy was related to seven construction products, while four of them also responded for around 80% of embodied GWP. Enlarging the database to encompass ten core products would increase coverage to over 93%. For cement and concrete, partial replacement of clinker by ground granulated blast furnace slag brought substantial reductions in the calculated values for all indicators but bWF, which unveils the effect of the water-intensive granulation process. Further research is expected to advance in LCI development and validation to enable the use of life cycle-based metrics to support decision-making within the national building sector.

**KEYWORDS** Life cycle indicators, embodied carbon, embodied energy.

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**RESUMO** O Anexo 57 da Agência Internacional de Energia (AIE) foi estabelecido para avançar na avaliação de energia e emissões de GEE associadas à construção de edificações. A avaliação de ciclo de vida auxilia no cálculo destes indicadores. Identificar os principais produtos de construção que descrevam tipologias construtivas-chaves tem um papel estratégico na otimização do monitoramento de indicadores e construção de inventários em contextos com práticas de ACV pouco consolidadas. Este artigo é dirigido por estas motivações. Nossos objetivos são: (i) calcular um conjunto selecionado de indicadores com base em ACV para descrever sinteticamente o desempenho ambiental de produtos de construção utilizados em três estudos de casos funcionalmente equivalentes; (ii) identificar os principais produtos contribuintes para a energia e carbono incorporados totais; e (iii) avaliar as implicações de se considerar $CO_2$ ou GWP (em $CO_{2e}$) incorporado. As métricas selecionadas incluem, além de EE e EGWP, abrangidas pelo Anexo 57: pegada de água azul (bWF), consumo de matéria prima não renovável (NRc) e emissão de compostos orgânicos voláteis (COVs). A modelagem dos ciclos produtivos utilizou dados próprios e dados secundários coletados na literatura ou adaptados de bases internacionais, mediante análise de similaridade com processos nacionais. Resultados de $CO_2$ e GWP incorporado foram obtidos pelos métodos de demanda acumulada de energia (CED) e CML 2001 baseline v. 2.05, respectivamente, e apresentados para os principais produtos contribuintes. NRc, bWF e COVs foram calculados diretamente a partir dos inventários e discutidos para cimentos e concretos. 80% da energia incorporada resulta de sete produtos de construção, enquanto quatro deles também respondem por pouco mais de 80% do GWP incorporado. A ampliação da base para abranger dez produtos aumenta esta cobertura para mais de 93%. Para cimento e concreto, a substituição parcial do clínquer por escória granulada de alto forno reduziu significativamente os valores de todos os indicadores considerados, exceto de bWF, que reflete o efeito do uso intensivo de água na granulação da escoria. Espera-se que pesquisas futuras avancem no desenvolvimento e validação de inventários e permitam o emprego de métricas de ciclo de vida na tomada de decisão no setor de construção brasileiro.

**PALAVRAS-CHAVE** Indicadores de ciclo de vida, carbono incorporado, energia incorporada.

## INTRODUCTION

The construction sector plays an increasingly important role on regional and global economies, contributing to the generation of job positions, to the development of new technologies and infrastructures and to enhance quality of life. That same greatness is observed in the environmental loads that arise from the building industry, extensively documented by authors like Bribrián, Capilla and Usón (2011).

Despite of its environmental relevance, the construction project performance has traditionally been measured in terms of quality, time and money spent (GANGOLELLS et al., 2009). The evaluation of environmental performance is relatively new and, because of that, still presents considerable methodological challenges that limit its practicability and reliability.

Environmental indicators are structured to capture resources usage and their consequent environmental impacts. They are designed to collect, process and use information aiming at making better decisions, at driving smarter political choices, and at measuring progress (WILSON; TYEDMERS; PELOT, 2007; JEFFERSON et al., 2007). Some indicators are shared by many industry sectors, such as $CO_2$ emission, and water and energy consumption (UNITED..., 2009). Buildings, however, are unique because of their decades long lifetime, multiple functions (BASBAGILL et al., 2013) and specificities, which call for a more oriented and complete set of indicators.

To assure reliability and thoroughness, calculation of indicators throughout the entire life cycle is of great importance. Life Cycle Assessment (LCA) stands out as a holistic tool to assess the potential environmental impacts throughout a product's life cycle (INTERNATIONAL..., 2006a). The wide and comprehensive scope of LCA is useful in order to avoid 'problem shifting', e.g. 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). Because of its systemic approach, LCA can scientifically support the calculation of more cohesive and consistent indicators.

Within the European Committee for Standardization, Technical Committee 350 (CEN TC 350), dedicated to developing standards on sustainability of construction works, published standard EN 15978 (EUROPEAN..., 2011b), which establishes a framework for providing building life cycle information. Impacts are distributed across four life stages (product, construction process, use and end of life), divided into sixteen modules (Figure 1).

The system boundary sets the interface between a building and its surroundings or other product systems. Depending on the approach adopted, the stages of production ('cradle to gate'); construction ('cradle to site' or 'cradle to handover', if construction activities are fully included); maintenance, repair, replacement and/or refurbishment (variations of 'cradle to use'); and end of life ('cradle to grave') are included or not in the assessment and metrics computation. In this sense, impacts can be determined as part (or selected life cycle modules) of the building's whole life environmental loads.

The International Energy Agency (IEA)'s Annex 57 (herein IEA-EBC Annex 57) was established in 2011, and is devoted to the identification, assessment and targeted control of the energy required for production, construction and maintenance of new buildings as well as for upgrading and subsequent maintenance of existing buildings. At the same time, the resulting impacts on the climate change (in terms of emissions and impact categories) are analyzed, evaluated and controlled using the metric of Global Warming Potential, expressed in units of carbon dioxide equivalent ($CO_{2e}$), to be in line with international standards, e.g. ISO 21929-1 (INTERNATIONAL..., 2011) and ISO/TS 14067 (INTERNATIONAL..., 2013).

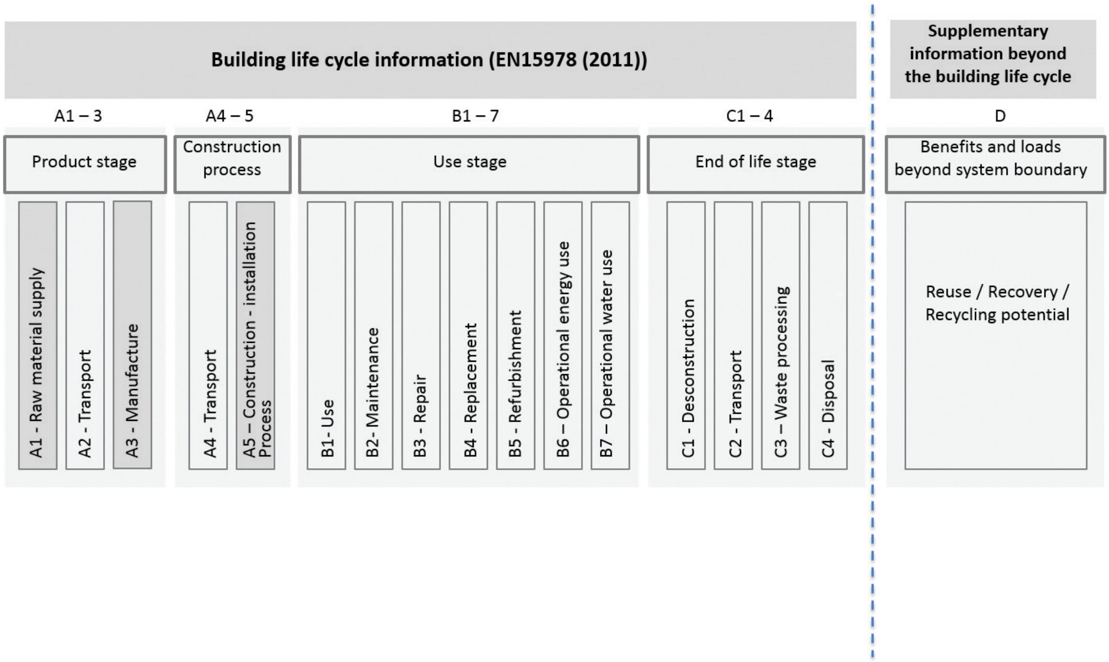


**Figure 1.** Building life cycle information stages and respective modules, according with EN 15978 (EUROPEAN..., 2011b). Darkened modules indicate the system boundary established for construction products' modeling in this study.

One of the key objectives that IEA-EBC Annex 57 pursues is the clarification of methodological issues related to the evaluation of 'embodied energy' and 'embodied $CO_2$ emissions/ GWP'. This includes definition of key concepts; of rules and recommendations for the system boundaries selection; of major methods for estimating 'embodied energy' and 'embodied GHG emissions' and for prescribing levels or benchmarks to measure building performance. Process-based, input-output or hybrid life cycle assessment (LCA) can support calculations of these indicators, but their application is still embryonic in Brazil. Identification of the major products that describe key building typologies plays a strategic role in the tasks of streamlining indicators' monitoring scope and LCI data gathering in contexts with little LCA practice consolidation. This paper is mostly motivated by Annex 57's backdrop, in which the authors participate, but enlarges its original scope to include calculation of other LCA-based indicators, which are relevant for the assessment of buildings.

Silva (2007) points out that Brazilian studies aiming at defining sustainability indicators for the construction sector are considerably variable and defined according to criteria and methodology that are not necessarily replicable. But indicators' definitions and calculations also vary throughout the world. Some of them show conceptual issues yet to be solved, as in the case of carbon emissions. Though the climate change impact category, expressed in terms of corresponding global warming potential (GWP, in $CO_{2e}$) is well established in the LCA field, communication of potential contribution of construction products and whole buildings to climate change still differs considerably. Wiedmann and Minx (2008) and ETAP (ENVIRONMENTAL..., 2007) defend that the carbon footprint should measure the amount of carbon dioxide emissions directly or indirectly caused by human activities or accumulated throughout a product's life cycle. On the other hand, POST (PARLIAMENTARY..., 2006) states that the indicator should represent the total amount of all greenhouse gases emitted during a product or process' life cycle. Such a discrepancy between definitions and calculation methodologies prevents direct comparability and may confuse interpretation. The recent ISO 14067 (INTERNATIONAL..., 2013) finally brought up a standardized concept for international use and defines carbon footprint as *the sum of greenhouse gas emissions and removals in a product system, expressed as* $CO_2$ *equivalents and based on a lifecycle assessment using the single impact category of climate change*.

Materials datasets usually disclose energy and carbon indicators in terms of environmental load per mass or volume unit of a given material. However, if those units do not provide the best functional description of material application into building systems and parts, they do not allow for comparison among alternatives competing to fulfilling the same functional requirement (e.g. area of roof, partition or flooring systems). Material selection decision-making shall rather consider impacts at whole building level (VERBEECK; HENS, 2010) and use the functional equivalency principle if any sort of comparison is intended.

As explained in the EN 15978 standard (EUROPEAN..., 2011b), assessments may be carried out on an individual object, but they will in most instances form part of the process for the evaluation of decisions *in relation to the object of assessment. Comparisons between the results of assessments of buildings or assembled systems (part of works)* shall be made only on the basis of their functional equivalency. The functional equivalent is a representation of the required technical characteristics and functionalities of a building or an assembled system, rationalized into a minimum description of the object of assessment. This description forms the basis for transparent and unbiased comparison.

The functional equivalent of a building or an assembled system shall include, but is not limited to, information on: *building type; relevant technical and functional requirements; pattern of use and required service life.* Other specific requirements and exposure to climate and to other local conditions may be also relevant, as well as regulatory and client's specific requirements or assumptions made, scenarios defined and the sources of information used by the assessor.

EN 15978 standard (EUROPEAN..., 2011b) also acknowledges the use of a *common unit of reference,* derived from the functional equivalent, for comparison of the assessment results of the buildings that have different functional equivalents. The choice of the common reference unit depends on a specific requirement of a technical, functional, environmental, social or economic aspect, or combination thereof, which is common to all these buildings and is linked to their corresponding functional equivalents. A common reference unit may be, for instance: *per* $m^2$, *per year, per employee or occupant, per room per year and per* $m^2$ *per year*.

Adopting 'unit of gross floor area (GFA)' as a common unit of reference to normalize indicators values is a convenient step that enables performance communication, establishment of design goals and comparison against individual products or whole building benchmarks. In fact, an increased number of recent and relevant studies (BLENGINI, 2009; BLENGINI; DICARLO, 2010; WALLHAGEN; GLAUMANN; MALMQVIST, 2011; PASSER; KREINER; MAYDL, 2012; KARIMPOUR et al., 2014; ROH et al., 2014; SAADE et al., 2014) has expressed environmental performance results per $m^2$ of built area for benchmarking purposes. Also in the policy making realm, though normalized benchmarks are unsuitable and absolute impact must be considered (JONES; HAMMOND, 2010), normalizing the indicators' values per unit of gross floor area eliminates the need to assess architectural plans for each building in a given region of consideration, facilitating guidance of policy decisions based on government data.

## MATERIAL AND METHODS

### *GOALS AND APPROACH OVERVIEW*

This paper aims at *(i)* calculating a selected set of LCA-based indicators to synthetically describe environmental performance of construction products for three functionally equivalent case studies; *(ii)* to detect the major contributors to embodied energy and carbon; and *(iii)* examining the implications of using two GHG emission accounting methods (embodied $CO_2$ *versus* embodied GHG emissions (global warming potential - GWP, in $CO_{2e}$) for communicating environmental performance of construction products. The selected metrics include – besides the embodied energy and carbon targeted by IEA-EBC Annex 57 - three other indicators that are relevant for environmental assessment of buildings, but have not yet reached standard consensus: the blue water footprint, non-renewable primary material consumption and volatile organic compounds (VOC) emissions.

Process-based life cycle assessment (LCA) provided the framework for metrics calculations. LCA is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (EUROPEAN..., 2011a). LCA was standardized by the ISO 14040 series (INTERNATIONAL..., 2006a, b, 2012, 2002). The method analyses all phases of a product and is an interactive process, composed by four stages (INTERNATIONAL..., 2006a): *(1)* goal and scope definition, in which the analysis purposes and comprehension are defined; (2) inventory analysis, which compiles and quantifies inputs and outputs for a product throughout its life cycle; (3) impact assessment, aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product ; and (4) interpretation, when the results of the analysis are presented.

The system boundary established for this study includes reference flows pertaining to modules A1, A3, and A5, shown in darker grey in Figure 1, and is in line with EN 15978 (EUROPEAN..., 2011b). Production cycles modeling used previously collected national data, as well as secondary data extracted from national literature or adapted from international databases whenever considered as reasonably similar to national processes (Table 1). SimaPro v.7.3 was the LCA support platform used.

From the metrics selected for use in the cases studied in this paper, only the climate change category and respective global warming potential (GWP) indicator is consistently encompassed by LCIA methods. Life cycle impact

**Table 1.** Inventory data sources and units defined for production processes modeling.

| Construction product | Units | Data source |
|---|---|---|
| **Concrete (fck 30)**[a] | 1 $m^3$ | Silva (2006) |
| **Portland cement (CPI-32, CPII-E-32, CPIII-32)**[a] | 1 ton | Silva (2006) |
| **Steel rebar, steel frame, wire, copper wire** | 1 ton | ELCD, version 2.0[b] |
| **PVC (conduit and tube)** | 1 ton | Industry Data, version 2.0[b] |
| **Wood (plywood; timber planks; roundwood)** | 1 $m^3$ | Ecoinvent, version 2.2[b] |
| **Sand, Gravel, Acrylic paint, Hydrated lime, Adhesive mortar, Ceramic tile** | 1 ton | Ecoinvent , version 2.2[b] |
| **Ceramic block** | 1 ton | Manfredini and Sattler (2005); Hammond and Jones (2011) |

[a]Concrete mixes with three amounts of ground granulated blast furnace slag (ggbs) as a clinker replacement were considered in this study (CPI-32 – 5%; CPII-E-32 – 30%; CPIII-32 – 66%); [b]adjusted to the Brazilian energy mix.

assessment (LCIA) methods aim at connecting each life cycle inventory (LCI) result (elementary flow or other intervention) to the corresponding environmental impacts. According to ISO guidelines, LCI results are classified into impact categories, each with a category indicator. The category indicator can be located at any point between the LCI results and the category endpoints (where the environmental effect occurs) in the cause-effect chain (JOLLIET et al., 2003).

Damage-oriented methods, such as Eco-indicator 99 (GOEDKOOP; SPRIENSMA, 2000) or EPS (STEEN, 1999a, b), try to model the cause-effect chain up to the damage (endpoint), sometimes paying the price of high uncertainties. On their turn, the classical (midpoint) impact assessment methods, such as CML (GUINÉE et al., 2002) and EDIP (HAUSCHILD; WENZEL, 1998), group LCI results in the so-called *'midpoint categories'*, using indicators that also characterize the elementary flows and other environmental interventions that contribute to a given impact, but are located somewhere between the LCI results and the damage (or endpoint) on the impact pathway. This limits uncertainties by restricting quantitative modeling to relatively early stages in the cause-effect chain. In this sense, using indicators derived from the inventory bears the same advantage, whenever further understanding and evaluation of the magnitude and significance of the potential environmental impacts are not pursued.

## CASE STUDIES AND FUNCTIONAL EQUIVALENCY DESCRIPTION

We have studied two public servicing buildings (one integrated service center, with 4.975,55 m² GFA, and one police-training center, with 1.511,74 m² GFA) and one public school building (4.869,23 m² GFA).

Even though the building type varied, and specific functional requirements might vary accordingly, there are no outstanding specific technical requirements that invalidate equivalency among the case studies: their design service life (50 years), exposure environment (coastal area, in the State of Espirito Santo), occupancy (similar fulltime-equivalent potential occupants) and use pattern (8 hours per day / 5 days per week), technical specifications and construction quality standard as per data collection in 2011/2012, structural requirements and overall construction typology (concrete-framed, horizontal (up to 3 floors), low window-to-wall ratio (WWR) buildings) represent typical practice for low-rise public buildings in the region and do suggest equivalency.

Building type-dependent functional requirements would be mostly related to the use stage, or too specific (e.g. abrasion class for flooring systems) and rather not captured by the average-data LCIs available. As we are piloting the use of a number of metrics on a small sample, restricting the analysis to the product stage and aiming at studying the process of generating average numbers for a certain class of buildings, the achieved equivalency level suits our purposes.

## RATIONALE FOR SELECTING INDICATORS AND CALCULATION METHODS

CEN TC 350 published standard EN 15804:2012 (EUROPEAN..., 2012), which determines the core rules for EPDs of construction products. From all environmental parameters listed in that standard, primary energy, global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP) and photochemical ozone creation potential (POCP) seem to be the most usually found. From these, primary energy is a resource intensity indicator; the remaining indicators refer to impact categories addressed by LCAs (SAADE et al., 2014).

Though listed as potential items to compose specific EPDs, metrics of water and non-renewable primary material consumption – both of them resource intensity indicators - do not have an agreed basis yet for European standardization [(EN 15978 (EUROPEAN… 2011b) and EN 15804 (EUROPEAN.., 2012)] and are less common in construction products' assessments, despite being fundamental to provide a thorough understanding of their impacts (SAADE et al., 2014). Furthermore, for most building-related applications, e.g. certification and rating systems, material impacts are often described in terms of regional, renewable, recycled or recyclable content, without tackling the key issue of mineral extraction rates directly (SILVA, 2007).

Consideration of volatile organic compounds (VOC) emissions is an attempt to advance from previous work focusing on resource use and ecosystem quality (SAADE et al., 2012; OLIVEIRA; SILVA; SILVA, 2013) and enlarge the assessment scope to include information on human health aspects. From the impact categories suggested by EN 15804:2012 that are more frequently found, POCP is the only one that alludes to human health issues. VOC emission is a major contributor to that photo-oxidant formation (GUINÉE et al., 2002), and can be totalized at a fraction of the effort needed to calculate POCP.

The selected set of metrics therefore comprises environmental impact indicators and resource use indicators, as defined by EN 15643-2 (EUROPEAN…, 2011a), and emissions (load) indicators. Resource use and emission indicators were directly derived from the inventories provided by Ecoinvent v. 2.2, Industry Data v.2.0 and ELCD v. 2.0 databases (item 2.5), avoiding reliance upon major assumptions or uncertainties usually associated to life cycle impact assessment (LCIA) methods (JOLLIET et al., 2003). Embodied energy was calculated by using the Cumulative Energy Demand (CED) method. The CED method computes the entire primary energy demand (or 'cumulative energy demand') that arises due to the production, use and disposal of an economic good. CED calculation is based on the method published by ecoinvent version 1.01, directly from the inventories. As implemented in SimaPro, characterization factors are given for the energy resources in five impact categories, expressed by the renewable (biomass, wind/solar/geothermal and water) and non-renewable (fossil and nuclear) CED components. No normalization is applied and each impact category is given the weighting factor 1 (GOMES et al., 2014). Embodied energy is herein expressed as total embodied CED, in MJ per unit (product) or per $m^2$ GFA (whole building).

We also used one environmental impact indicator, embodied GWP (expressed in $CO_{2e}$ per unit (product) or per $m^2$ GFA (whole building), which was calculated by using the CML 2001 baseline v. 2.05 method (item 2.6). The CML method, developed in 2001 at the Institute of Environmental Sciences (CML) at Leiden University (GUINÉE et al., 2002), gathers several impact categories, including climate change, for which results are straightforwardly expressed in units of carbon dioxide equivalent emissions per functional unit, after multiplying the mass of each GHG emission by its equivalency factor (GOMES et al., 2014). As single-category indicators, embodied energy and embodied GWP could have also been computed directly from the inventory, but we have benefited from applying CED and CML automatic calculations.

## LCA GOAL AND SCOPE DEFINITION

SimaPro v.7.3 was the support platform used to perform *cradle to gate* LCAs following ISO 14040 (INTERNATIONAL..., 2006a) methodological guidelines, covering processes from raw material extraction to the factory's gate, excluding freight transport within the supply chain and to the construction site. As this study focuses on obtaining average results for the product stage, case-specific transport, as well as subsequent life cycle stages (construction, use and end of life), were disregarded.

System boundary definition for the cradle to gate LCAs considered cut-off rules given in EN 15804:2012 (EUROPEAN..., 2012), which admit that, in case of insufficient input data or data gaps for a given unit process, materials and processes can be omitted if the process contributes with less than 1% of total mass or renewable or non-renewable primary energy, and all excluded materials and processes do not exceed 5% of total energy use and mass. Due to this paper's motivation, we have used, mass, embodied primary energy and carbon as cut-off filters to identify the construction products for which the remaining metrics would be calculated.

## LIFE CYCLE INVENTORY ANALYSIS: CALCULATION OF LCI-DERIVED INDICATORS

The (volume or mass) units used for deriving the impact factors for the construction products considered reflect designers and quantity surveyors' common practice. Corresponding data sources are summarized in Table 1.

Consumption of each construction product was totalized for the case studies. 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. Reference flows (median values) shown in Table 2 were compiled from the bill of materials and shop drawings, corrected using national estimates for onsite construction wastage (AGOPYAN et al., 1998) and normalized by $m^2$ GFA.

An ISO standard to guide calculations of water footprints of products is still under development (INTERNATIONAL..., 2014). Our blue water footprint calculation then follows the definition given in a comprehensive procedure for water footprint (WF) assessment (HOEKSTRA et al., 2011), which encompasses three major components: blue WF (ground and surface water used); green WF (rainwater used) and grey WF (freshwater polluted). We applied a filter on the LCI that adds together the consumption of different ground and surface water sources over a product's life cycle (Equation 1).

**Table 2.** Reference flows (median values) compiled for the sample studied.

| Material/component | unit | Consumption/$m^2$ GFA[a] |
|---|---|---|
| **Sand** | kg | 902.25 |
| **Gravel** | kg | 574.41 |
| **Portland cement CP III-32** | kg | 282.09 |
| **Concrete (fck 30)** | $m^3$ | 0.27 |
| **Steel rebar** | kg | 17.63 |
| **Steel frame** | kg | 4.89 |
| **Ceramic block** | kg | 72.07 |
| **Ceramic roof tile** | kg | 0.00 |
| **Planed dried wood** | $m^3$ | 0.01 |
| **Raw dried wood** | $m^3$ | 0.00 |
| **Plywood** | $m^3$ | 0.00 |
| **PVC tube** | kg | 1.19 |
| **PVC conduit** | kg | 0.99 |
| **Adhesive mortar** | kg | 3.32 |
| **Hydrated lime** | kg | 6.53 |
| **Ceramic tile** | kg | 2.46 |
| **Copper wire** | kg | 0.10 |
| **Acrylic paint** | L | 0.42 |
| **PVA paint** | L | 0.19 |
| **Architectural glazing** | kg | 1.29 |

[a]Median value of three case studies.

Analogously, non-renewable consumption calculation sums the life cycle intake of mineral resources (Equation 2), while the VOC indicator totalizes all methane and non-methane VOC emissions listed in the life cycle inventory (Equation 3).

$$bWF = Q\,x\left(\sum_{i=1}^{n} bW_i \;per\,unit\right) \tag{1}$$

*Where:*

*bWF is the blue water footprint, in m³/m² GFA*

*Q is the consumption of a given construction product (median value of cases studied)*

*bW is blue water consumed from a ground or surface source over the product's life cycle*

*n is the number of blue water sources identified in the product's LCI*

$$NRc = Q\,x\left(\sum_{i=1}^{n} NR_i \;per\,unit\right) \tag{2}$$

*Where:*

*NRc is the non-renewable primary material consumption, in kg/m² GFA*

*Q is the consumption of a given construction product (median value of cases studied)*

*NRi is the non-renewable primary material consumed over the product's life cycle*

*n is the number of different types of non-renewable primary materials identified in the product's LCI*

$$VOC = Q\,x\left(\sum_{i=1}^{n} VOC_i \;per\,unit\right) \tag{3}$$

*Where:*

*VOC is the volatile organic compounds emission, in kg VOC/m² GFA*

*Q is the consumption of a given construction product (median value of cases studied)*

*VOC is the volatile organic compounds emitted over the product's life cycle*

*n is the number of VOC emission types identified in the product's LCI*

The embodied $CO_2$ calculation followed the same procedure of filtering $CO_2$ emissions from each construction product's inventory (Equation 4). Given the lack of information on ceramic blocks in the available LCI databases, $CO_2$ data was extracted from University of Bath's inventory of carbon and energy (HAMMOND; JONES, 2011). We acknowledge that the energy mix in the UK and Brazil are different, and that such a difference can imply in less accurate results. However, the methodological thoroughness applied to ICE database suggests its use as a proxy at this time.

$$ECO_2 = Q\,x\left(\sum_{i=1}^{n} CO_{2i} \;per\,unit\right) \tag{4}$$

Where:

*$ECO_2$ is the embodied $CO_2$, expressed in kg $CO_2$ emissions per m² GFA*

*Q is the consumption of a given construction product (median value of cases studied)*

*$CO_2$ is the carbon dioxide emissions over the product's life cycle*

*n is the number of $CO_2$ emission sources identified in the product's LCI*

Finally, the embodied energy calculation was computed by the CED method, which totalizes all primary energy inputs over a given item's life cycle

(Equation 5). Given the already mentioned lack of data related to ceramic blocks in LCI databases, national data from Manfredini and Sattler (2005) were then used, for their methodological approach was explicit and found suitable for this paper's purposes.

$$EE = Q\,x\left(\sum_{i=1}^{n} E_i \; per\,unit\right) \tag{5}$$

Where:

*EE is the primary energy embodied in construction products, in MJ/m² GFA*

*Q is the consumption of a given construction product (median value of cases studied)*

*E is the primary energy consumed over the product's life cycle*

*n represents the number of primary energy sources identified in the product's LCI*

## *LIFE CYCLE IMPACT ASSESSMENT: CALCULATION OF LCIA-DERIVED INDICATOR*

The embodied GWP was calculated using CML 2001 v.2.05, which multiplies the mass of emitted GHGs by their corresponding equivalency factors (Equation 6).

$$EGWP = Q\,x\left(\sum_{i=1}^{n} GWP_i \times m_i \; per\,unit\right) \tag{6}$$

*Where:*

*EGWP stands for embodied Global Warming Potential, in mass of* $CO_{2e}$*, of extraction/manufacturing of the construction product*

*Q is the consumption of a given construction product (median value of cases studied)*

*GWP is the Global Warming Potential equivalency factor for each greenhouse gas (GHG) considered by CML 2001 v.2.05*

*n is the number of GHG considered*

*m is the specific GHG emission, in mass, per building product unit*

# RESULTS PRESENTATION AND DISCUSSION

## *EMBODIED ENERGY*

Figure 2 presents the median values of embodied energy (total cumulative energy demand, CED) of construction products per m² GFA. 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, 5%; CP II-E-32, 30% and CP III-32, 66%), consistently with Brazilian standards (ASSOCIAÇÃO..., 1991a, b, c). Portland cement here indicated was not used to manufacture concrete, which was delivered ready mixed, but applied in the production of other cement-based elements.

As expected and well documented in literature, our results show that Portland cement and concrete are the main contributors to the sample's median embodied energy profile. International studies usually investigate the performance of ordinary Portland cement, which is composed primarily by clinker, with little or no mineral admixtures and would be equivalent to Brazilian CP I-S-32. In Brazil, however, CP II-E-32 (30% of ground granulated blast furnace slag) is the most commercially available cement type, while CP

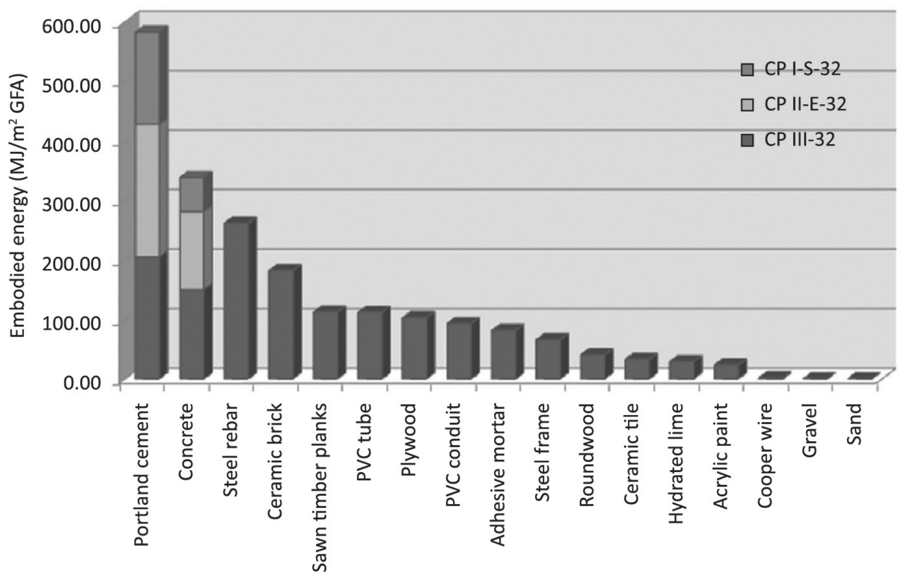


**Figure 2.** Embodied energy (total CED) of construction products, in MJ per m² GFA.

III-32 (66% of ground granulated blast furnace slag) is the top seller type in the sample building's region.

Figure 3 considers concrete as broken down into its constituents, which were added to cement, sand and gravel used in other applications. About 80% of the total embodied energy was cement, steel rebar, ceramic block, sawn timber, PVC tube, plywood, and PVC conduits.

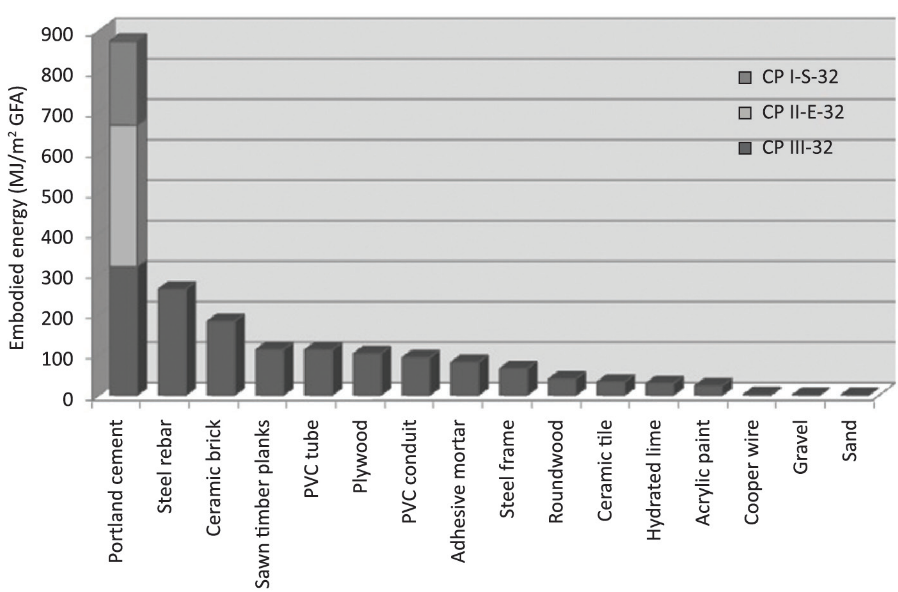


**Figure 3.** Embodied energy of construction products per m² GFA after concrete's breakdown into basic constituents and addition to those used in other services.

### *EMBODIED $CO_2$ AND EMBODIED GWP*

Figure 4 presents the median values of embodied $CO_2$ of construction products per m² GFA, while Figure 5 presents the median values after concrete constituents were broken down and added to cement and aggregates used in other services. The top four contributions (cement, steel rebar, ceramic block, PVC tubes) respond for over 80% of the sample's median embodied $CO_2$.

Figure 6 presents the median values found for embodied GWP, for all quantified materials, and Figure 7 presents the results after concrete was

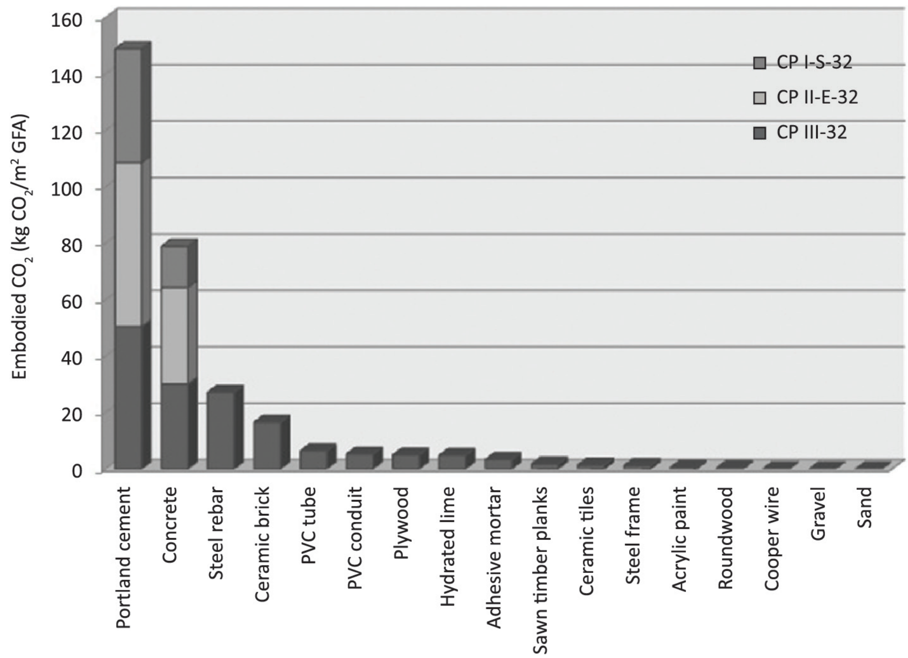


**Figure 4.** Embodied $CO_2$ of construction products per m² GFA.

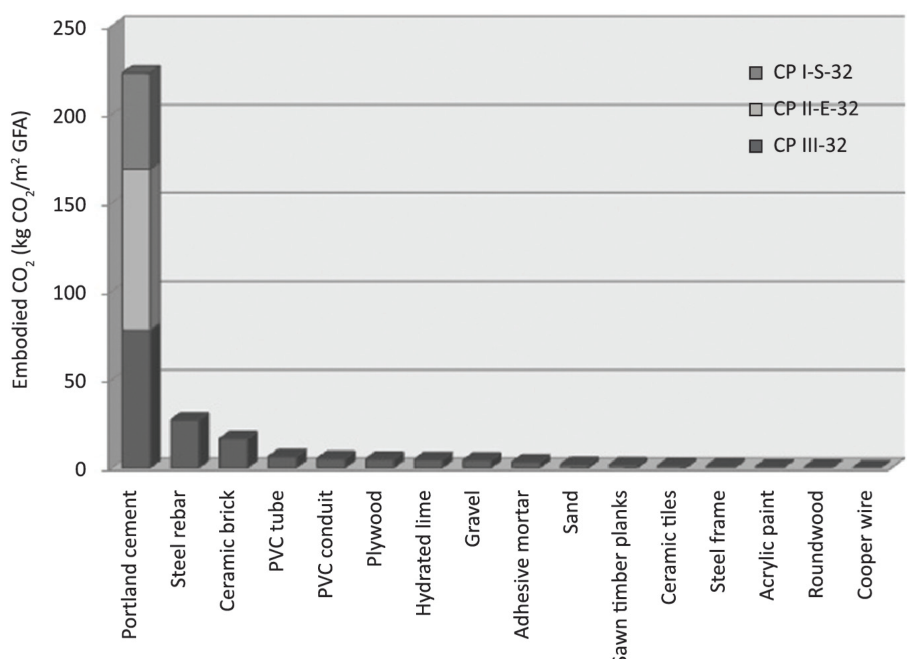


**Figure 5.** Embodied $CO_2$ of construction products per m² GFA, after concrete's breakdown into basic constituents and addition to those used in other services.

broken down into its constituents and correspondent cement, sand and gravel were added to those used in other applications.

Comparative analysis between Figures 4-5 and Figures 6-7 indicates that inclusion of the remaining GHG emissions in the calculation did not substantially change the products' contribution ranking, but considerably increased the indicator's absolute values for some products.

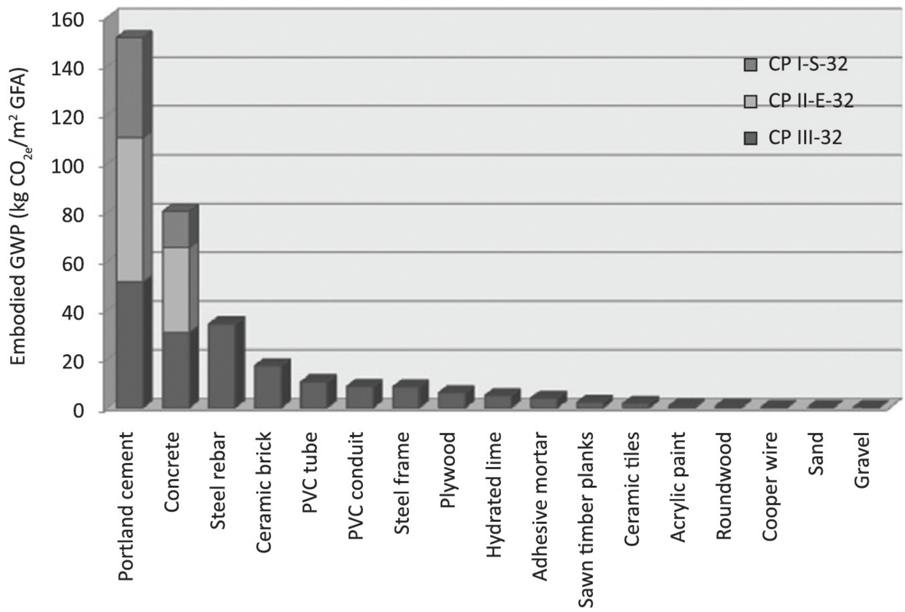


**Figure 6.** Embodied GWP of construction products, in $CO_{2e}$ per m² GFA.

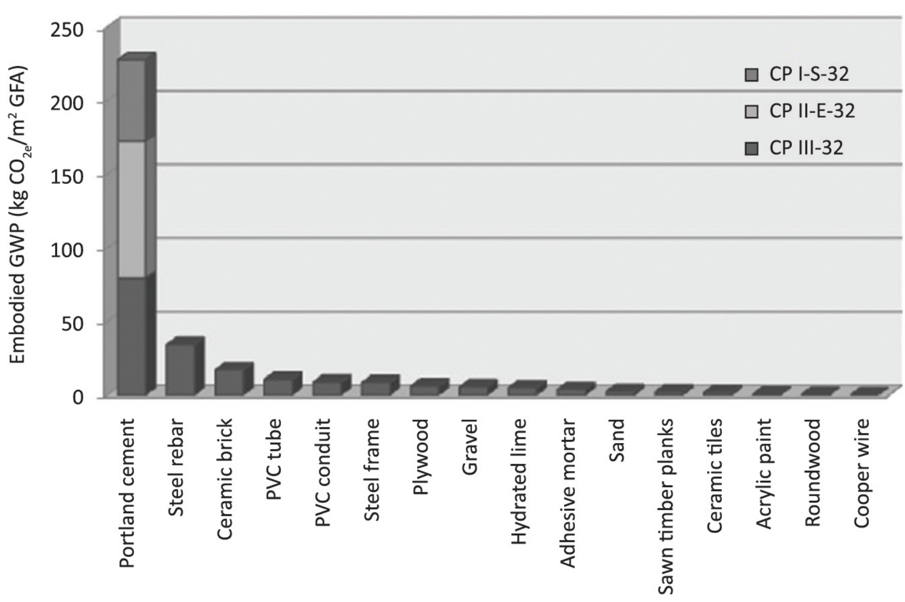


**Figure 7.** Embodied GWP of construction products, in $CO_{2e}$ per m² GFA, after concrete's breakdown into basic constituents and addition to those used in other services.

The top 4 contributors for the buildings' embodied $CO_2$ and GWP were always the same: Portland cement, steel rebar, ceramic block and PVC tubes. These products collectively respond for over 80% of overall embodied values. Adoption of different carbon accounting methodologies merely shifted positions among the top 10 contributors, which would still respond for roughly 98% of total embodied carbon.

Still, three major groups of construction products regarding embodied $CO_2$ and GWP became very clear:

- $CO_2$ proportion in GHG emissions is **above 95%,** namely: cement, ceramic block and hydrated lime. For this group, embodied $CO_2$ would pretty much represent the embodied GHG emissions;

- $CO_2$ proportion in GHG emissions is **between 80%-95%**, including plywood, roundwood, sand, ceramic roof tile, and adhesive mortar; which might be considered enough to be a reasonable GHG descriptor for specific applications or preliminary screening; and
- $CO_2$ proportion in GHG emissions is **between 60% and 80%**, comprising steel rebar, PVC tube and conduit, gravel and roof steel structure; for which contribution of non-$CO_2$ GHG cannot be neglected.

These results confirm that adopting embodied $CO_2$, for all construction products, as a rule of thumb descriptor of climate change impact can clearly mislead conclusions.

Even though $CO_2$ and GWP measure different things, and variation in absolute values is expected, both metrics have been used to describe contribution to climate change. As the focus should be kept on the effect (climate change), considering only $CO_2$ portraits partial results, with consequences that are more critical for some construction products than for others. This is particularly important considering that Brazilian official data on some building materials with the highest GWP (e.g. cement and steel) are only published in terms of $CO_2$, while their contribution to climate change is actually higher. Using available $CO_2$ information to describe contribution of a whole building to climate change therefore poses the risk of importantly underestimate it. We therefore strongly endorse ISO 14067:2013 proposition that GWP is used, and recommend that corresponding data for national construction products is pursued.

## *DISCUSSION ON THE CORE INDICATORS RESULTS FOR CEMENT AND CONCRETE*

Values of embodied energy (EE), embodied $CO_2$ (EC), embodied GWP (EGWP), blue water footprint (bWF), non-renewable primary material consumption (NRc) and Volatile Organic Compounds emissions (VOC) per unit of gross floor area were calculated for cement and concrete, the two larger contributors to the building's total embodied energy and embodied $CO_2$ / GWP (Table 1). Table 2 presents the indicators' values per $m^2$ GFA found for concrete with CP I-S-32, CP II-E-32 and CP III-32. Values within parenthesis indicate reductions in relation to CP I-S-32, kept for international reference.

For both concrete and cement, the potential benefit that arises from using ggbs as a clinker replacement becomes evident. The embodied $CO_2$ and the embodied GWP diminished considerably when comparing CP III-32 to CP II-E-32 and even more to CP I-S-32, as the ggbs content increased from 5% (CP I-S-32) to 30% (CP II-E-32) and 66% (CP III-32) and corresponding types of concrete. The embodied energy, the non-renewable primary material consumption and the VOC emissions indicators also presented significant reductions, which confirm potential environmental advantages of replacing clinker with ggbs in cement/concrete manufacturing. These findings might find resonance in improvement of technical properties consistently pointed out in literature (CAMARINI, 1995; SILVA, 1998, 2006; TANESI, 2010).

In the other hand, the blue water footprint value increased when ranging from CP I-S-32 to CP III-32 (Table 3), and from concrete with CP I-S-32 to concrete with CP III-32 (Table 4). The observed raise is due to water consumption on the blast furnace slag granulation process, a known water intensive industrial procedure. Most steelmaking companies have water reuse programs in place, which would reduce cement and concrete's blue water footprints due to the use of ggbs as a clinker replacement. As in this paper we worked with and aimed at aggregated data and results, water reuse programs were not considered, due to the unpredictable differences across steelmaking companies' environmental management programs.

**Table 3.** Environmental indicators calculated for cement types CP I-S-32, CP II-E-32 and CP III-32.

| | EE (MJ/m²) | $ECO_2$ (kg/m²) | EGWP (kg/m²) | bWF (m³/m²) | NRc (kg/m²) | VOC (kg/m²) |
|---|---|---|---|---|---|---|
| **CP I-S-32** | 873.50 | 223.37 | 227.75 | 0.134 | 511.16 | 5.28E-4 |
| **CP II-E-32** | 666.06 (-23.75%) | 169.08 (-24.30%) | 172.44 (-24.29%) | 0.763 (+82.44%) | 392.99 (-23.12%) | 4.64E-4 (-12.1%) |
| **CP III-32** | 316.53 (-63.76%) | 77.92 (-65.12%) | 79.56 (-65.07%) | 1.443 (+90.71%) | 184.85 (-63.84%) | 3.58E-4 (-32.2%) |

**Table 4.** Environmental indicators calculated for concrete with cement types CP I-S-32, CP II-E-32 and CP III-32.

| | EE (MJ/m²) | $ECO_2$ (kg/m²) | EGWP (kg/m²) | bWF (m³/m²) | NRc (kg/m²) | VOC (kg/m²) |
|---|---|---|---|---|---|---|
| **Concrete w/ CP I-S-32** | 338.00 | 78.93 | 80.64 | 0.846 | 720.70 | 0.0019 |
| **Concrete w/ CP II-E-32** | 281.09 (-16.84%) | 64.37 (-18.45%) | 65.79 (-18.42%) | 1.036 (+18.34%) | 661.69 (-8.19%) | 0.0018 (-5.26%) |
| **Concrete w/ CP III-32** | 150.23 (-55.55%) | 30.16 (-61.79%) | 30.93 (-61.64%) | 1.345 (+37.10%) | 596.78 (-17.19%) | 0.0017 (-10.50%) |

## CONCLUSIONS

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 indicators' definitions and calculation methods. Those differences can mislead interpretations and disclosure, especially when the calculation methods are not explicit, increasing risk of cumulative errors.

Another limitation arises from the deficiency of reference LCI data. In this paper, the lack of national data related to some relevant materials required the use of multiple international databases, further complemented by third-party published literature in the case of ceramic block. We acknowledge that, though not ideal for solid result aggregation and benchmarking, it was unavoidable and the most reasonable alternative in our case. That said, once transparency is ensured, this is a procedure frequently adopted to fill in data gaps in the LCA realm worldwide, and consistently observed in its application to building studies.

The indicators analyzed were selected based upon their environmental relevance and measurability, and represent a core collection of metrics to allow swift but meaningful assessments in scenarios of early implementation of environmental design accountancy.

Consideration of VOC emission was explored here as an initial attempt to advance from previous work focusing on resource use and ecosystem quality and enlarge the assessment scope to include information on human health aspects. VOC emission is a major contributor to photo-oxidant formation and can be totalized at a fraction of the effort needed to calculate POCP. Since PCOP communicates effects on human health in a more comprehensible way than VOCs, examination of their relationship seems worth to be resumed in future investigations.

Focusing on a certain building typology represented by three case studies, results enables preliminary benchmarking against national and international reported results and feeding of design tools to empower environmental modeling and documentation. Around 80% of the total embodied energy was related to cement, steel rebar, ceramic block, sawn timber, PVC tube, plywood, and PVC conduits, while cement, steel rebar, ceramic block and

PVC tube responded for around 80% of embodied GWP. Enlarging the core database to include adhesive mortar, steel profiles (roof support structure) and roundwood would increase coverage to over 93% and provide a very sound description of the buildings' embodied energy and GWP profiles. These results complement conclusions by Saade et al. (2012) for embodied energy and can play an strategic role in the tasks of streamlining indicators' monitoring scope and LCI data gathering in the Brazilian context, still with little LCA practice consolidation.

Except for bWF, calculated values for all other indicators decreased considerably with increased ggbs content, suggesting important environmental advantages of ggbs as clinker replacement in cement production. Determining if the identified environmental benefits overcome water usage impacts is out of scope of this paper. The presently available multi-category impact assessment methods do not include water usage, which would make it impossible to reach an unambiguous aggregated result. Furthermore, impact analysis beyond the so-called 'midpoint' embed a series of assumptions and uncertainties, which imply in a great deal of subjectivity inherent to the weighting attribution across categories.

The uniform basis for the development and publication of environmental product declarations (EPDs) in some countries has contributed significantly to the improvement of the data availability for international construction products related to embodied energy, GWP and other environmental metrics. Unfortunately we are not in the same pace in Brazil yet. Among our next research steps are the investigation of additional material intensity/dematerialization indicator; database expansion to include other building typologies and increase the number of cases assessed within them; and expansion of system boundary to cover whole life of individual buildings. We expect that, following a coordinated methodological outline, future works will gradually evolve to constitute an LCI database of the most relevant construction products, and enable the use of the proposed metrics, as well as of LCA as a whole, to support decision-making in the Brazilian construction sector.

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