

Methodological discussion and piloting of Life Cycle Assessment – LCA-based environmental indicators for eco-efficiency of Brazilian building materials

Discussão metodológica e aplicação piloto de critérios de Avaliação de Ciclo de Vida – ACV, como indicadores de eco-eficiência de materiais de construção no Brasil

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Abstract Water consumption, energy consumption and CO₂ emission are indicators common to many industry sectors. Less common - but relevant - indicators are the non-renewable content and the Volatile Organic Compounds emissions. Life Cycle Assessment – LCA can support calculations of these indicators, but is still embryonic in Brazil. This paper main goals are (i) proposing a set of LCA-based indicators to assess eco-efficiency of building materials per unit of built area, (ii) analyzing differences between embodied CO₂ and embodied CO_{2eq} of Brazilian building materials, and (iii) verifying calculation feasibility of proposed indicators based upon four case studies. Data for materials/components production cycle modeling were collected from national literature or adapted from SimaPro 7.3 built-in Ecoinvent database. Results showed that, for the studied building typologies, 80% of the total embodied energy were related to cement, steel rebar, ceramic brick, sawn timber and plywood, while the ranking for the embodied CO₂ changed, showing that 89% of the total value was related to cement, ceramic brick, steel rebar, PVC tubes and conduits. Therefore, a core database for about ten materials provides a reasonable description of the building embodied energy and CO₂ profile, corresponding to 98%, in both cases, of total values. For cement and concrete, partial replacement of clinker by ground granulated blast furnace slag brought substantial reductions of proposed indicators. Proposed further research is expected to contribute to constitute a Lyfe Cycle Indicators – LCI database that enables the use of the proposed metrics, and reinforces the advantages of using LCA as a decision-making tool in the national building sector.

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

Resumo O consumo de água e de energia e emissão de CO₂ são

indicadores comuns a muitos setores da indústria. Indicadores menos comuns, porém relevantes, são os conteúdos não renováveis e as emissões de Compostos Orgânicos Voláteis –COV. A Avaliação de Ciclo de Vida - ACV pode fundamentar cálculos para esses indicadores, mas ainda é um processo embrionário no Brasil. Este trabalho tem como objetivos principais: (i) propor um conjunto de indicadores baseados em ACV para avaliar a eco-eficiência dos materiais de construção por unidade de área construída, (ii) analisar as diferenças entre CO₂ incorporado e CO_{2eq} incorporado em materiais de construção do Brasil, e (iii) a verificação de viabilidade do cálculo dos indicadores propostos com base em quatro estudos de caso. Os dados para modelagem de ciclo de produção de materiais / componentes foram coletados a partir da literatura nacional ou adaptados da base de dados SimaPro 7.3 built-in Ecoinvent. Os resultados mostraram que, para as tipologias construtivas estudadas, 80% do total da energia incorporada estavam relacionados com cimento, vergalhões de aço, tijolo de cerâmica, madeira serrada e compensados, enquanto o *ranking* para o CO₂ incorporado mudou, mostrando que 89% do valor total estava relacionado com cimento, tijolo cerâmico, vergalhões de aço, tubos de PVC e condutas. Portanto, uma base de dados central por aproximadamente dez materiais fornece uma descrição razoável do perfil de energia incorporada à construção e de CO₂ incorporado, que correspondem a 98% de valores totais em ambos os casos. Para cimento e concreto, substituição parcial do clínquer por escória granulada de alto-forno trouxe reduções substanciais de indicadores propostos. Investigações posteriores propostas deverão contribuir para constituir um banco de dados de Indicadores de Ciclo de Vida - ICV que permita o uso das métricas propostas, e reforçam as vantagens da utilização ACV como uma ferramenta de tomada de decisão no sector nacional da construção civil.

Palavras-chaves: indicadores, LCA, carbono incorporado, energia incorporada, setor de construção.

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: 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 (ANE 2008); and a great part of anthropogenic carbon emissions come from building activities.

Despite of its environmental relevance, the construction project performance has traditionally been measured in terms of quality, time and money spent (Gangoles *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. 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.

The variability within indicators' definition is observed throughout the world. There are still conceptual issues observed in many cases, especially regarding carbon emissions. Wiedmann and Minx (2008) and ETAP (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 (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 reveals that the calculation methodology is still quite irregular, and that results from different authors may be opposed, and lead to mistaken conclusions.

According to Jefferson *et al.* (2007), 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. 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 common to many industry sectors such as water consumption, energy consumption and CO₂ emissions (UN 2009). Buildings, however, are unique because of their

decades long lifetime and multiple functions (Basbagill *et al.* 2009), which calls for a more oriented and complete set of indicators.

Building material consumption is often described in terms of regional, renewable, recycled or recyclable content. Previous research (Saade *et al.* 2012), however, showed that a less common but far more relevant indicator is non-renewable content, which communicates the depletion intensity of abiotic resources. In the current scenario, in which data regarding the operational phase (use and maintenance) of the built environment are, many times, inaccurate and subjective, the consideration of Volatile Organic Compounds (VOC) emissions during the manufacturing phase might be a possible alternative to consider health-related indicators in building sustainability assessment.

Environmental indicators are commonly disclosed at materials and components level, which, at a building level, might mislead conclusions. Decisions should be made by taking into consideration the materials and components impacts on the performance of the entire building (Verbeeck and Hens 2010), which can be done through normalization of indicators per unit of built area.

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 lifecycle (ISO 2006). According to Finnveden *et al.* (2009), 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. Because of its systemic approach, LCA can scientifically support the calculation of more cohesive and consistent indicators.

This paper aims at (i) proposing a set of life cycle-based indicators, to assess material eco-efficiency of buildings per unit of built area (m²), (ii) analyzing the differences between two methods for carbon footprint calculation on results of building materials environmental performance, and (iii) verifying calculation feasibility of the proposed indicators, based upon three case studies.

Methods

Research steps

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 four case studies, the two main research target were (i) to identify the building materials/components with the largest potential contribution to the building's embodied energy and CO₂; and (ii) to calculate blue water footprint, abiotic (non-renewable) content, and volatile organic compound emissions for the materials/components with the largest contributions, as found in item i.

The performed LCAs followed ISO 14040:2006 (ISO 2006)

methodological guidelines, and fall into the cradle-to-gate category. The embodied energy and the embodied CO₂ per unit of built area (m²) were the initial filters applied to define the material/components for which the other proposed metrics would be calculated.

Quantification of materials/components mostly used in three case studies

Total usage of material/components was quantified for four low-rise (up to 3 floors) buildings, with low window-to-wall ratio, reinforced concrete-framed, masonry façade and partitions, and ceramic or metallic roofing buildings. The case studies comprise one integrated service center (4.975,55 m²); one police-training center (1.511,74 m²); and two school buildings (4.869,23 m² and 2963,08 m²). To consider typical reusability, consumption of plywood, sawn planks and raw timber was divided by a factor of four. 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, and divided by the total built area and corrected by national estimates for construction waste (Agopyan *et al.* 1998).

Calculation of the embodied energy and embodied carbon indicators

The embodied energy indicator (EE) was calculated using the construction materials and components' LCI provided by the utilized support platform, except for the ceramic brick value, which was obtained from Manfredini and Sattler (2005), whose adopted methodological approach was explicit and seemed reasonably close to the one herein proposed. Different values of primary energy sources are found in the inventory. By adding these values, the EE value per previously defined functional unit was found.

To assess the differences between embodied CO₂ and embodied CO_{2eq} emission on final results, the first scenario considered CO₂ emission only, while the second scenario (CO_{2eq}) included emission of all greenhouse gases (GHGs). For the sake of efficiency and practicality, the 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.

The embodied CO₂ and embodied CO_{2eq} per functional unit were calculated from the inventory analysis for each material/component, except for the ceramic brick value, which was obtained from University of Bath's inventory of carbon and energy (Hammond and Jones 2011). Though these authors used an electricity grid that differs from the Brazilian energy mix, and such a difference can imply in less accurate results, the methodological thoroughness observed in their research suggests its use as a potential proxy, given the lack of data related to that specific component in national and international LCI databases.

Functional unit adopted for each material/component, and the data sources used for production process modeling are shown in Chart 1.

Chart 1 Inventory data source and functional unit defined for each material/component considered in the study.

Construction materials and components	Functional unit	Data source
Concrete (fck 30) ^a	1 cubic meter	Silva (2006)
Portland cement (CPI-32, CPII-E-32 e CP III-32) ^a	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 brick	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%; CP III-32 – 66%).

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

For each material/component, blue water footprint (bWF), abiotic (non-renewable) content (NRc) and Volatile Organic Compound emissions (VOCe) per functional unit were calculated from the inventory analysis. For the blue water footprint calculation, the consumption of different water sources during the extraction and production was totalized. For abiotic (non-renewable) content calculation, the consumption of mineral resources throughout the product's life cycle was added. The VOCe indicator was calculated through the sum of all (both methane and non-methane) VOC emissions listed in the inventory.

Results and discussion

Embodied energy per unit of built area

The median values of embodied energy of building materials and components per m² of built area are shown in Figure 1. 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%), consistent with Brazilian standards (ABNT 1991a, 1991b, 1991c). Portland cement here indicated was not used to manufacture concrete, which was delivered ready mix, but applied in the production of other cement-based elements.

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 that international studies usually investigate the performance of ordinary

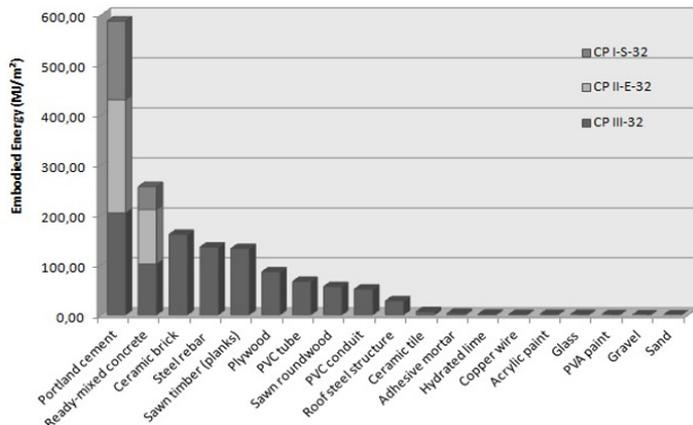


Figure 1 Embodied energy of materials and components per m² of built area, updated from Saade *et al.* (2012).

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 most widely commercially available, while CP III-32 (66% of ground granulated blast furnace slag) is the top selling cement in the region of this study.

The concrete broken down into its constituents, which were added to cement, sand and gravel used in other applications are shown in Figure 2. Materials/components top 10 ranking would be therefore composed by cement, ceramic brick, steel rebar, sawn/planed timber, plywood, PVC tubes, sawn/raw timber, PVC conduits, roof steel structure, ceramic tiles and adhesive mortar.

The median values of embodied CO₂ of materials and components per m² of built area are shown in Figure 2, while the median values after concrete constituents were broken down and added to cement and aggregates used in other services are shown in Figure 4.

The top five contributions (cement, steel rebar, ceramic brick, PVC tubes and conduits) respond for over 80% of the total embodied CO₂ (Figure 4). This shift in ranking of major contributors in relation of embodied energy is quite plausible, since CO₂ embodied in wood products is knowledgeably lower than that of many materials.

The median values found for embodied CO_{2eq} for all quantified materials are shown in Figure 5, and the results after concrete was broken down into its constituents and correspondent cement, sand and gravel were added to those used in other applications are shown in Figure 6.

The comparison between Figures 3 and 4 with Figures 5 and 6 indicates that, although the ranking did not substantially change, the

Table 1 Environmental indicators calculated for cement types CP I-S-32, CP II-E-32 and CP III-32.

	EE (MJ/m ²)	EC (kg/m ²)	EC _{eq} (kg/m ²)	bWF (m ³ /m ²)	NRc (kg/m ²)	VOCe (kg/m ²)
CP I-S-32	827.12	124.76	125.80	0.11	421.25	4.34E-4
CP II-E-32	625.79 (-24.34%)	94.05 (-24.62%)	94.95 (-24.53%)	0.62 (+82.17%)	319.05 (-24.26%)	3.75E-4 (-13.57%)
CP III-32	294.13 (-64.44%)	45.53 (-65.11%)	44.17 (-64.89%)	1.34 (+91.74%)	150.62 (-64.25%)	2.68E-4 (-38.36%)

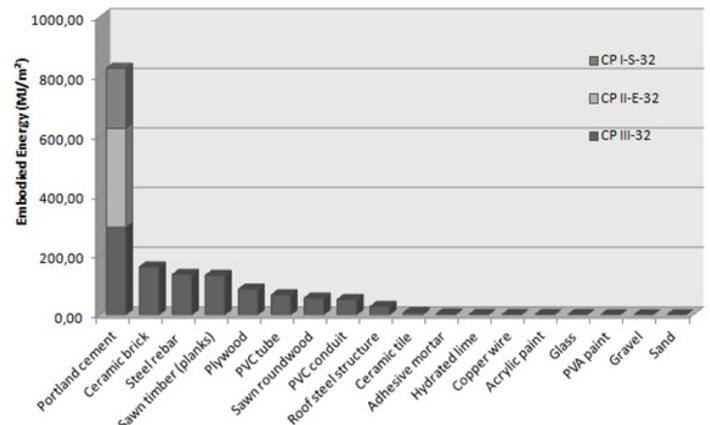


Figure 2 Embodied energy of materials and components per m² of built area after broken down into concrete's.

indicator's absolute value changed considerably, as expected when including other emissions in the calculation. Such an increase can influence final results, especially when the calculation methods are not explicit, which could lead to results' improper disclosure and use.

Discussion on proposed core set of environmental indicators

Values of embodied energy (EE), embodied CO₂ (EC), embodied CO_{2eq} (EC_{eq}), blue water footprint (bWF), abiotic (non-renewable) content (NRc) and Volatile Organic Compounds emissions (VOCe) per unit of built area were calculated for cement and concrete, the two larger contributors to the building's total embodied energy and embodied CO₂ / CO_{2eq} (Table 1). The indicators' values per unit of built area found for concrete with CP I-S-32, CP II-E-32 and CP III-32 are shown in Table 2. Values within parenthesis indicate reductions in relation to CP I-S-32, kept for international reference.

For both concrete and cement, the benefit that arises from ggbs as a clinker replacement becomes evident. The embodied CO₂ and the embodied CO_{2eq} 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). The same conclusions can be withdrawn for the analyzed types of concrete. The embodied energy also presented a significant reduction, as did the abiotic (non-renewable) content and VOC emissions indicators, which confirms the environmental advantages of replacing clinker with ggbs in cement/concrete manufacturing.

In the other hand, the blue water footprint indicator presented an increase when ranging from CP I-S-32 to CP III-32,

Table 2 Environmental indicators calculated for concrete with cement types CP I-S-32, CP II-E-32 and CP III-32.

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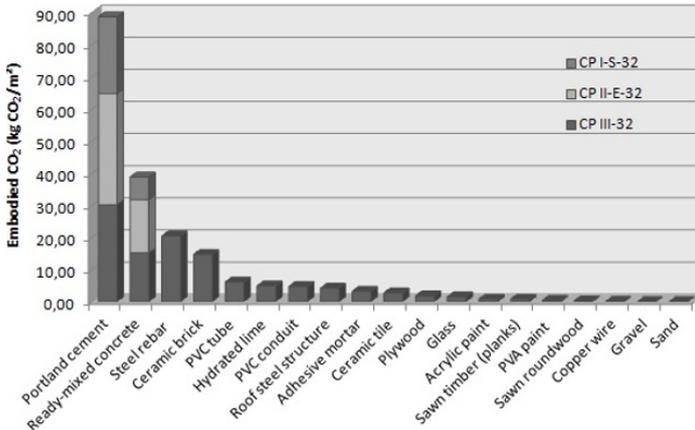


Figure 3 Embodied CO₂ of materials and components per m² of built area.

and from concrete with CP I-S-32 to concrete with CP III-32. 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, which would reduce cement and concrete's blue water footprints due to the use of ggbs as a clinker replacement. In this paper, however, water reuse programs were not considered, because of the unpredictable differences between steelmaking companies' environmental management programs.

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

Another possible limitation arises from the deficiency of national and international reference data for insertion in LCA platforms. In this paper, the lack of data related to some relevant materials led to the use of other data sources, which though not the best procedure for comparison and aggregation was acknowledged as the most reasonable alternative.

For the building's embodied energy the top 5 contributors were Portland cement, ceramic brick, steel rebar, timber planks and plywood; while for the building's embodied carbon timber planks

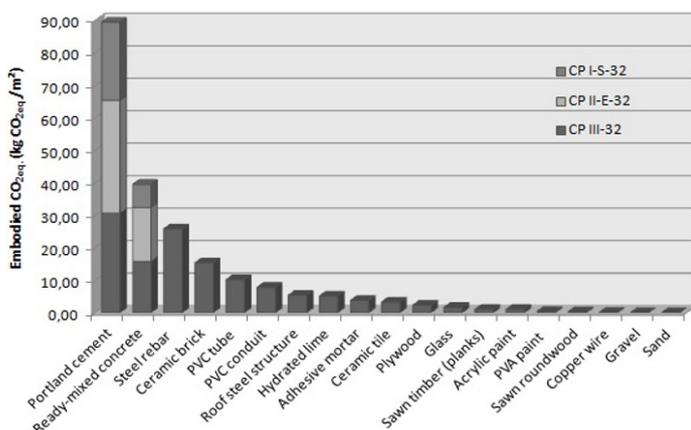


Figure 5 Embodied CO_{2eq} of materials and components per m² of built area.

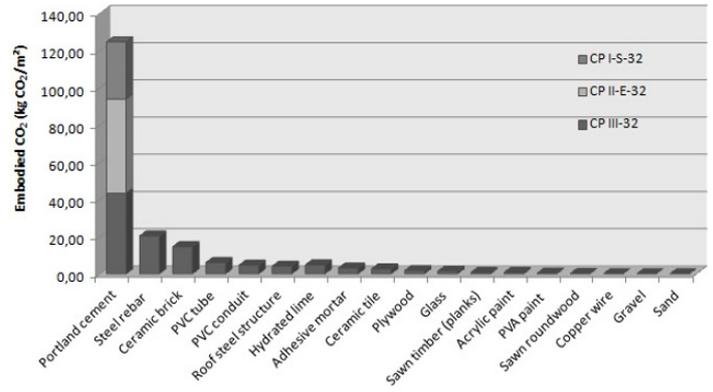


Figure 4 Embodied CO₂ of materials and components per m² of built area, after concrete's cement and aggregates were added to those used in other services.

and plywood were replaced by PVC tubes and conduits, regardless the carbon methodology adopted. However, contrasting embodied CO₂ and embodied CO_{2eq} results found in this paper show how adoption of different methodologies varied the absolute values achieved for the studied materials/components. Even though absolute values change when shifting from embodied CO₂ to embodied CO_{2eq}, the top 10 materials/components still correspond to approximately 98% of total embodied carbon values, in both methodologies. Therefore, similarly to findings by (Saade *et al.* 2012) for embodied energy, a core database encompassing ten materials or so can provide a very reasonable description of the building embodied CO₂ / CO_{2eq} profiles, and possibly streamline indicators monitoring scope.

Except for bWF, increased due to the water-consuming granulation process, indicators proposed reflected the environmental advantages of ggbs as clinker replacement in cement production, and decreased considerably with increased ggbs content. These findings complement improvement of some technical properties consistently pointed out in literature (Camarini 1995, Silva, 1998, Hill and Sharp 2002, Silva 2006, Guneyisi *et al* 2007, Chidiac e Panesar 2008, Tanesi 2010).

Next research steps include investigation of additional material intensity/dematerialization indicator and database expansion to include other building typologies. It is also expected that, following a coordinated methodological outline, future works evolve to gradually constitute an LCI database of the most relevant building materials and components, to enable the use of the proposed metrics, as well as LCA methodology as a whole, as decision-making tools.

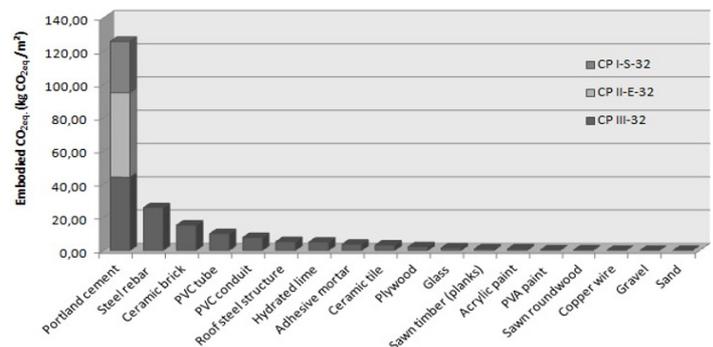


Figure 6 Embodied CO_{2eq} of materials and components per m² of built area, after concrete's cement and aggregates were added to those used in other services.

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