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"Gheorghe Asachi" Technical University of Iasi, Romania

ASSESSING THE GREENHOUSE GAS EMISSIONS OF BUILDINGS IN BRAZIL: A CASE STUDY OF A HOUSING COMPLEX

João Gabriel Lassio*, David Castelo Branco, Alessandra Magrini

Energy Planning Program of the Federal University of Rio de Janeiro, Avenida Horácio de Macedo, 2030, Bloco C-211, Cidade Universitária, Rio de Janeiro-RJ 21941-914, Brazil

Abstract

Buildings play a central role in the low-carbon future and pose challenges for integration with sustainable development, especially in Brazil, where urban areas are still expanding and the implementation of environmental tools, such as Life Cycle Assessment (LCA), faces more difficulties. The aim of this paper is to assess the greenhouse gases (GHG) emissions during the whole life cycle of a housing complex located in Rio de Janeiro, Brazil. For this purpose, a life cycle-based analysis was carried out to estimate the GHG emission from the production of the most commonly used building materials, such as steel, cement, ceramic, wood, among others; transport activities; and the construction, use (energy consumption during 50-year useful life), maintenance and demolition of the housing complex. According to the results, the GHG emissions generated during the housing complex's life cycle are 282.62 tCO_2eq, which can be expressed as 1,009.34 kg $CO_2eq./m^2$/50-year or 20.19 kg $CO_2eq./m^2$/year. These emissions are dominated by the use stage (56%), which is followed by the pre-use (30%) and end-of-life (14%) stages. Indirect emissions accounted for more than half of GHG emissions (57%), mainly driven by emissions from building materials (85.47 t $CO_2eq.$; or 30%). Cement was responsible for 22% of embodied GHG emissions from building materials. These findings are relevant to the Brazilian context in which environmental issues have not determined the choice of building materials. Furthermore, this paper supports the improvement of the LCA usefulness in Brazil as it contributes to the mitigation of the lack of national datasets.

Key words: building materials, greenhouse gases, life cycle approach, residential building

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1. Introduction

The value chain of the building industry significantly alters the environment. Mining, quarrying, transporting of raw materials, and manufacturing of building products not only deplete natural resources and generate pollution in the air, water, and soil but also require considerable energy consumption with its associated greenhouse gas (GHG) emissions (Berge et al., 2009; Cruz et al., 2019; Lippiatt et al., 2007). This sector is responsible for an estimated 40% of the world's annual raw materials consumption and approximately 40% of global yearly energy use (Hrabovszky-Horváth and Szalay, 2014; IPCC, 2014; Nejat et al., 2015; Uttam, 2014). Buildings-related GHG emissions have more than doubled since 1970, representing 10% of all GHG emissions in 2010 (IPCC, 2014). The situation is similar in Brazil, where the building industry is responsible for an estimated 44% of final energy consumption, 9% of GHG emissions, and 45 million tonnes of construction and demolition waste (CDW) collected per year (ABRELPE, 2018; Lauriano, 2013).

Climate change is recognized as one of the main adverse effects of buildings since these are closely linked with our society's total carbon footprint (Fenner et al., 2018; Lei et al., 2020). Dealing with this global phenomenon has been a critical challenge of our present time because it will impact almost every human system. Accordingly, most current

* Author to whom all correspondence should be addressed: e-mail: joao.gabriel@ppe.ufrj.br; Phone: +55 21 39388761; Fax: +55 21 39388777

sustainability strategies are inherently associated with reducing our overall carbon footprint (Fenner et al., 2018).

In a situation in which the population growth and the continuous migration to urban areas merge, new buildings emerge as a central piece of a low-carbon future and an obstacle to moving towards sustainable development (IPCC, 2014; UN, 2019). This situation is particularly acute in developing countries, such as Brazil, where urban areas are still expanding (Brazil, 2018). Its median level of urbanization is projected to rise from 87% in 2018 to 92.4% in 2050 (UN, 2019).

Only by analysing GHG emissions throughout the whole value chain of buildings is it possible to keep track of performances of their key life cycle stages and components. In this context, the Life Cycle Assessment (LCA) is particularly interesting, and such an environmental tool requires consistent and reliable data. One of its first steps is the Life Cycle Inventory (LCI) analysis which consists of the materials and energy inputs and outputs associated with products, processes, and services (Gursel et al., 2014). There have been some difficulties in disseminating LCA in Brazil mainly because of the limited number of locally appropriate datasets (Ribeiro and Silva, 2010). Many LCIs have been developed in other countries considering boundaries and scopes reflecting their contexts. Most of them do not fulfil the need for representative data of many Brazilian materials and processes (Ribeiro and Silva, 2010). As a result, foreign LCI databases' usage is inappropriate and may lead to errors above 50% (Lenzen, 2001).

According to Ibn-Mohammed et al. (2013) and the International Energy Agency (IEA) (2016), embodied emissions of buildings in different countries can vary from 2% to 80%. For instance, there are significant discrepancies among amounts of CO_2 emitted during the cement production process, ranging from 652 to 920 kg CO_2/t_{cement} (Kajaste and Hurme, 2016). These emissions stem mostly from fuel combustion and limestone calcination. They tend to be higher or lower depending mainly on whether the national energy matrix is less clean or cleaner, respectively (Fairbairn et al., 2012). Since the Brazilian electricity mix is largely made up of hydropower, CO_2 emissions from cement production tend to be reduced (Ribeiro and Silva, 2010).

In order to address this situation, some studies should be conducted to modify foreign LCI database (Gursel et al., 2014); and to analyse the significant inputs and outputs related to key building typologies for simplifying LCI data collection in contexts with little LCA practice consolidation (Hong et al., 2015; Lu and Wang, 2019; Lu et al., 2017; Saade et al., 2014; Su et al., 2016). Of all these previous works, Saade et al. (2014) is the only one focused on the Brazilian context. Even so, the authors employed not only national data but also data collected from international literature or adapted from foreign databases.

The present paper is part of a comprehensive project on the sustainability of the building sector in Brazil and corresponds to its start point by addressing the GHG emissions associated with residential buildings. With this aim in mind, a life-cycle analysis was carried out to assess the GHG emission from a housing complex located in São Gonçalo, Rio de Janeiro, using a Brazilian dataset. This analysis takes into account the most commonly used building materials (such as steel, cement, ceramic, wood, etc.); transport activities; and construction, use (energy consumption during 50-year useful life), maintenance and demolition of the housing complex.

2. Methods

2.1. Carbon footprint

The methodology employed in assessing GHG emissions from the case study building is based on the requirements and guidelines for quantifying and reporting the carbon footprint of a product established by ISO 14067 (2018). Carbon footprint is a life cycle-based approach that considers the GHG emissions associated with the whole value chain of a product. For buildings, this method encompasses the direct and indirect GHG emissions which stem from all building materials and the construction, use, maintenance, and end-of-life stages of buildings' life cycle (Hong et al., 2015).

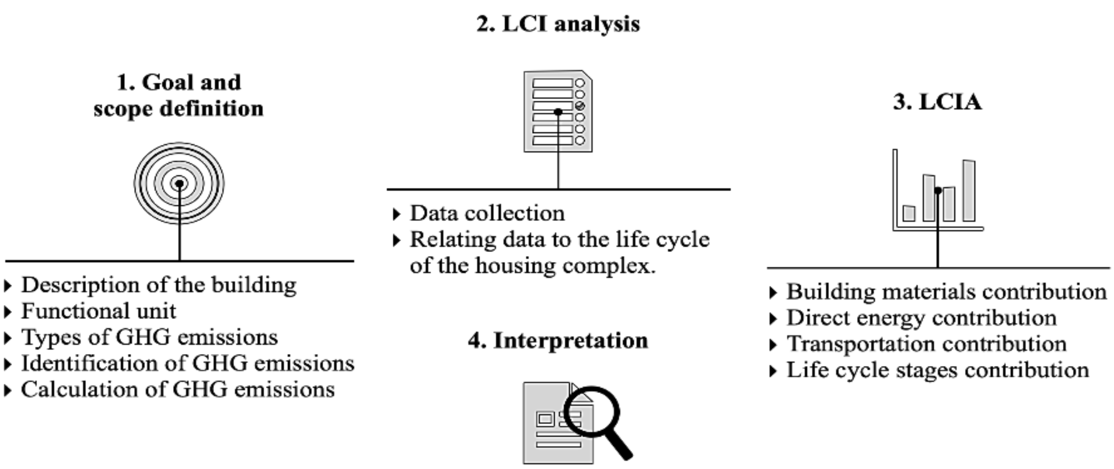

Fig. 1. Methodology employed in assessing GHG emissions from the case study building

According to ISO 14067 (2018), performing a carbon footprint analysis consists of the following steps: (i) goal and scope definition, (ii) LCI analysis, (iii) life cycle impact assessment (LCIA), and (iv) interpretation. Hence, the estimation and assessment of GHG emissions of the case study building followed the steps described in Fig. 1.

3. Case-study presentation

3.1. Goal and scope definition

3.1.1. Description of the building

This paper examines a housing complex located in the city of São Gonçalo, Rio de Janeiro, which is composed of five conventional single-family dwellings for the lower middle class. Each dwelling consists of two floors with a living room, kitchen, utility area, one bathroom, two bedrooms, garage, and a yard, corresponding to a built-up area of 56 m² on average (Fig. 2). The construction of this housing complex makes use of traditional materials and predominant Brazilian construction methods, resulting in a reinforced concrete structure with masonry sealing closure of ceramic bricks.

3.1.2. Functional unit

To support a fair and suitable quantitative comparison of the functions performed by different buildings, the functional unit of the system under study was defined by a unit of living area (1 m^2) per year.

3.1.3. System boundaries

In this paper, the system boundaries were set according to a cradle-to-grave approach. Fig. 3 illustrates the three key life cycle stages defined to the housing complex (pre-use, use, and end-of-life) linked to five main anthropogenic processes (extraction of raw materials, production and distribution of building materials, transport activities, and CDW management).

The pre-use stage concerns the processes involving the construction of the housing complex, raw material extraction, building materials production, and transport activities (Fig. 3). Table 1 shows that the present paper addresses the elements of structure, masonry, floor and wall coverings, ceiling, door and window frames, and roofing. Regional materials were considered and their amounts were estimated from the original building drawings. Regarding specifically sand, hydraulic lime, cement, ceramics, and gravel, it was assumed a value chain in which such materials are extracted and manufactured on the same site.

Contemplating the use of building materials, products and equipment, subsidiary activities, and CDW generation, the construction of the housing complex takes in all nine months. In this process, the energy consumption was divided into electricity consumption by workers and construction equipment. The first one was estimated using the simulator of electricity consumption from the local electric company (Light and Power Company, 2019). The second one was calculated by utilizing the data from the 13th edition of the Prices Composition Tables for Budgets (TCPO) (2012), which is characterized as one of the most reliable databases supporting the Brazilian building construction budgets.

For the foundation and structure systems, a concrete of 21 MPa produced at the construction site and conventional wooden formworks for their molding (without taking into account shoring components) were taken into account. In that respect, it is worth mentioning that this paper considers a clinker/cement ratio of 0.68 and formworks reused five times during their life cycle (SNIC and ABCP, 2019).

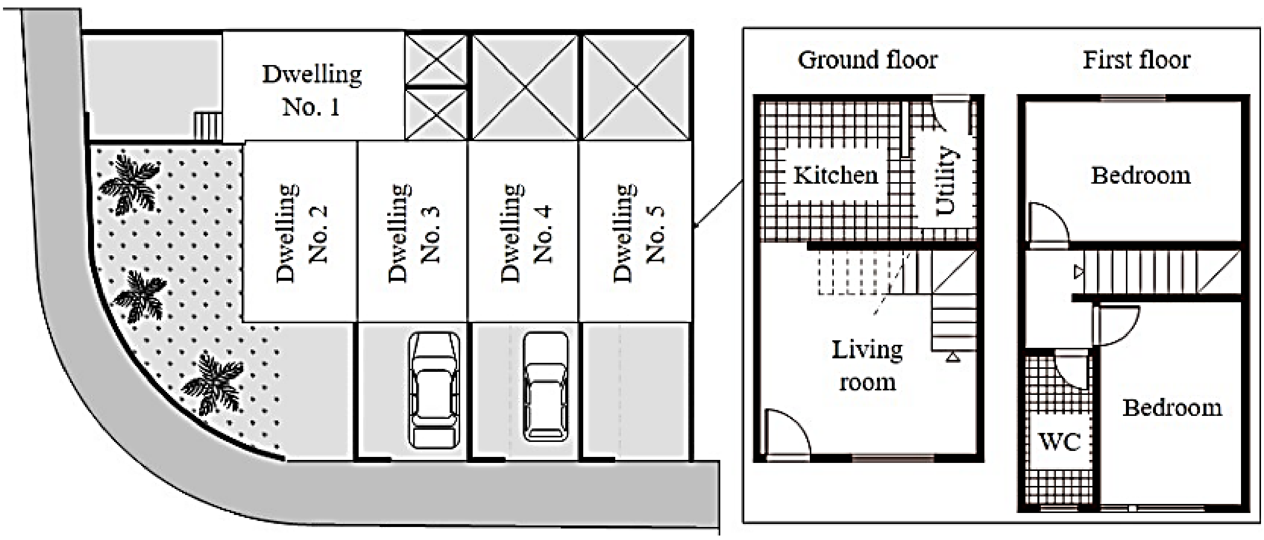

Fig. 2. Housing complex plan view

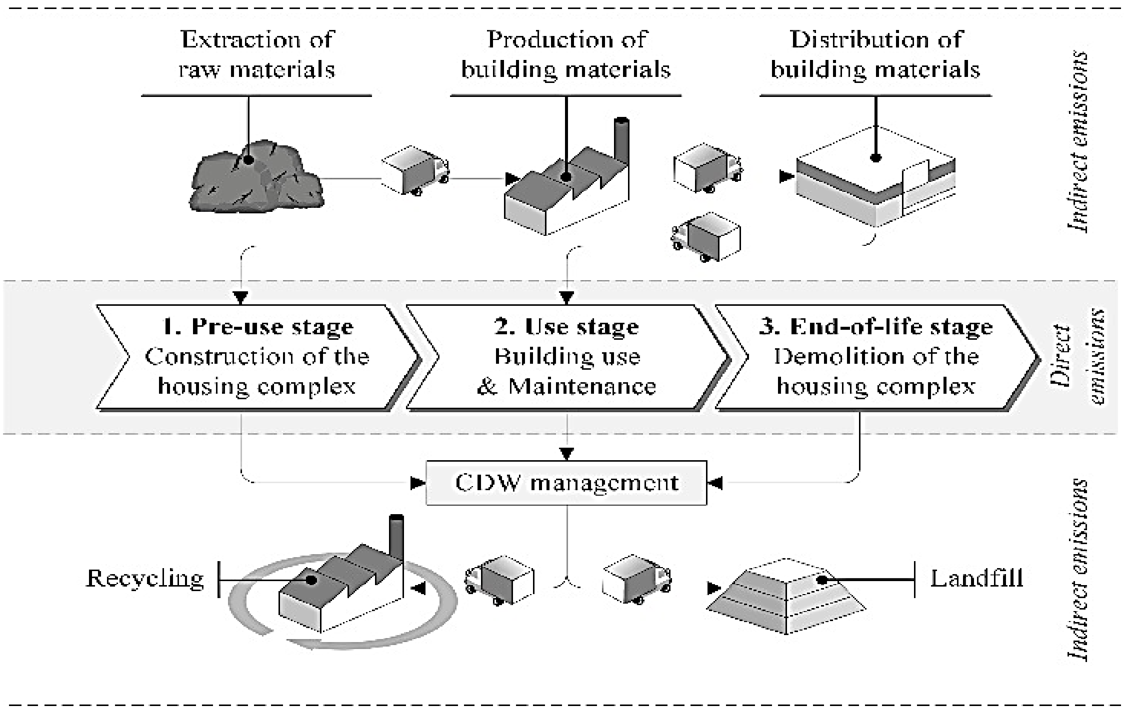

Fig. 3. Life cycle boundaries

The floor and wall covering system use an industrial adhesive mortar, while the masonry and door and window frames systems use a mortar produced in the construction site. For all materials, except wood, an estimation of material losses during the construction process was carried out by analysing literature data (Agopyan et al., 2003). Furthermore, one-third of the wood was assumed to be derived from native forests, i.e., from deforestation (Costa, 2012; Uhlig et al., 2008).

Use stage encompasses the processes which are related to the operation of the housing complex over 50 years. This period includes operating energy consumption related to entertainment, cooling (without air-conditioning), lighting, cleaning, laundry, and cooking. The information on energy use was based on estimated calculations with electric and gas natural companies, resulting in 10 m³ of natural gas and 256.40 kWh of electricity per month. Considering that some facilities need changes or enhancements to continue to be useful or functional, the use stage also includes maintenance and retrofitting interventions in the 25 years of the life of the housing complex with similar environmental issues as in the construction process (ABNT, 2008; Woolley, 2013; Wu and Low, 2013). This paper contemplates the floor and wall covering, ceiling, door and windows frames, and roofing systems since the other systems tend to have a superior useful life than the one defined for the building. As in the construction process, losses in the form of solid waste generated by the replacement of components were included in the use stage.

As the last step, the end-of-life stage inventories the demolition of the housing complex and the final disposal of CDW. Processes involved in this stage are scenario-based. Despite the Brazilian regulatory recommendations (Capello, 2006), the high generation of CDW – one of the heaviest and most voluminous wastes generated in the country – associated with the absence or shortcomings of management systems contributes to illegal disposal in landfills and wastelands (ABRELPE, 2018; IPCC, 2006; Simion et al., 2013). Accordingly, most CDW is not currently recycled in Brazil. However, there is a general agreement that the National Policy for Solid Waste Management (Brazil, 2010) combined with the resolutions established by the Brazilian Environmental Council (CONAMA) (2002; 2012), which aim to enhance CDW management, will raise the national CDW recycling rates in the future (John and Angulo, 2013). In this way, recycling rates (from 25% to 50%) were adopted for all building materials, depending on the nature of CDW (Table 2).

Given that all stages of the housing complex's life cycle generate CDW, the end-of-life scenario described in Table 2 covers all of them (Fig. 3). Note that the building construction process produces CDW not only from the use of wood forms but also from losses and wastes occurring during the services' execution. The use stage generates CDW from the maintenance intervention and the losses and wastes arising during its execution. Lastly, the end-of-life stage corresponds to the generation of CDW from the demolition of the housing complex.

Transportation is necessary for displacements between the different life cycle stages. In the present paper, these displacements are made only by road transportation as the road network predominates in Brazil.

Note that the displacements between the extraction of raw materials sites and the production of building materials sites were estimated using the distances between existing well-known industrial sites in the country.

Table 1. The building systems and their characteristics and materials

Building system	***Characteristics***	***Materials***
Foundations and structure	Reinforced concrete structure	Steel, sand, gravel, cement, and wood (formwork system)
Masonry	Ceramic bricks blocks and building mortar	Sand, hydraulic lime, cement and ceramics
Floor and wall covering	Flooring and wall ceramic tiles and adhesive mortar	Sand and adhesive mortar
Ceiling	Gypsum boards	Gypsum
Door and windows frames	Wooden doors and windows	Steel, sand, hydraulic lime, cement, wood and glass
Roofing	Two slopes, ceramic tiles, and wooden structure	Steel, ceramics, and wood

Similarly, transport activities in the end-of-life stage consider the distances between the housing complex and the already existing landfill and recycling plant in the city (Fig. 4). Regarding the distribution of building materials, a displacement of 10 km was assumed based on the average distance between the main existing suppliers in the city and the construction site.

Table 2. The end-of-life scenario

Material	***CDW rate (%)***	***Destination***
Sand, gravel, hydraulic lime, ceramics, and cement	25	Recycling
	75	Landfilling
Steel, wood, and glass	50	Recycling
	50	Landfilling

3.1.4. Types of GHG emissions

Among the seven major GHG in terms of radiative forcing, the three most important are: CO_2, methane (CH_4), and nitrous oxide (N_2O). GHG emissions such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are rarely found in the building construction activities (Saade et al., 2014).

3.1.5. Identification of GHG sources

From the definition of the system boundaries, Table 3 identifies and classifies GHG emissions. Direct GHG emissions stem from activities that occur in situ, whereas indirect ones refer to embodied emissions in building materials and services necessary to the housing complex's construction. It is worth pointing out that the latter type is often neglected by studies and may include extraction and production processes, transport activities, and CDW management (Vares et al., 2019).

3.1.6. Calculation of GHG emissions

The most common simple methodological approach for calculating GHG emissions consists of using the information on human activity, named activity data (AD), combined with factors that quantify emissions per unit activity, called emission factors (EF). Global warming potential (GWP_{100}) should also be taken into account for this calculation, translating the global warming effect of a specific gas *i* over a 100-year time horizon into a common unit, so-called CO_2 equivalent (CO_2eq.).

Therefore, the estimation of GHG emitted over the 50-year lifetime of the case study building is based on Eq. 1 (IPCC, 2007).

$$E = \sum_{i=1}^{n}(AD \times EF_i \times GWP_i) \quad (1)$$

3.1.6.1. GHG emissions from building materials

Regarding building materials, the anthropogenic GHG emissions associated with their energy embodied are estimated by multiplying the primary energy consumption from different fuel sources by its emission factors. Moreover, GHG emissions from chemical reactions in industrial processes are especially relevant in the building industry as producing cement, chemicals, and non-ferrous metals leads to the inevitable release of significant emissions regardless of energy supply (IPCC, 2007). In this way, the calculation of GHG emissions from extraction and production processes of building materials is performed as per Eq. (2).

$$E_{j,i} = \left[\sum_{f=1}^{F}(PE_{f,j} \times EF_{f,i}) + \sum_{r=1}^{R} EF_{r,i}\right] \times W_j \quad (2)$$

where $\boldsymbol{E_{j,i}}$ is the emission of the specific GHG *i* associated with extraction and production of the building material *j* (in tonnes); $PE_{f,j}$, primary energy consumption from the fuel source *f* associated with the extraction and production of the building material *j* (in GJ per tonne); $EF_{f,i}$, the emission factor of the fuel source *f* concerning the gas *i* (in tonnes per GJ); *F*, the number of fuel sources; $EF_{r,i}$, the emission factor of the chemical reaction *r* concerning the gas *i* (in tonnes of *i* per tonne of *j*); *R*, the number of chemical reactions; and W_j, the weight of the building material *j* (in tonnes).

3.1.6.2. GHG emissions from direct energy consumption

As previously mentioned, the energy demand comprises energy consumption not only for staff activities and construction site equipment during construction processes but also for entertainment, cooling, lighting, cleaning, laundry, and cooking during building operation. Thus, the GHG emissions from direct energy consumption are calculated as given by Eq. (3).

$$E_{s,i} = UL \times \sum_{s=1}^{S} EC_s \times EF_{s,i} \quad (3)$$

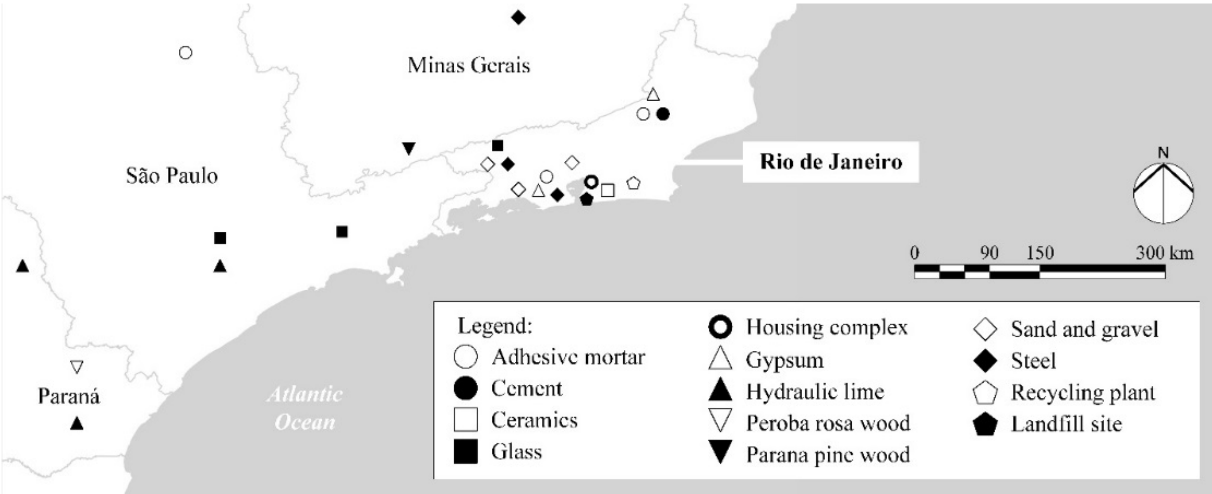

Fig. 4. Existing industrial plants considered

Table 3. GHG emissions sources

Stage	*Direct emissions*	*Indirect emissions*
Pre-use	Energy consumption of staff activities and construction site equipment	Extraction of raw materials; manufacturing and distribution of building materials; transport activities; and CDW management
Use	Consumption of electricity and natural gas	Extraction of raw materials; manufacturing and distribution of building materials; transport activities; and CDW management
End-of-life	-	CDW management

where $E_{s,i}$ is the emission of the specific GHG i associated with direct energy consumption from the energy source s (in tonnes); UL, the useful life of the housing complex (in years); EC_s refers to the estimation of the energy used from the energy source s over a period of one year (in GJ per year); S is the number of energy sources involved in direct energy consumption; and $EF_{s,i}$ corresponds to the emission factor of the energy source s concerning the gas i (in tonnes per GJ).

3.1.6.3. GHG emissions from transportation

Since transportation is necessary for displacements between the different stages throughout the life cycle of a building, the estimation of GHG emissions from transportation of building materials is performed as expressed by Eq. (4).

$$E_{t-j,i} = DIST \times CON_{diesel} \times W_j \times EF_{diesel,i} \quad (4)$$

where $E_{t-j,i}$ is the emission of the specific GHG i associated with transportation of the building material j (in tonnes); $DIST$, distance travelled (in km); CON_{diesel}, diesel consumption estimation for the distance travelled (in litres per tkm); W_j, the weight of the building material j (in tonnes); and $EF_{diesel,i}$, the emission factor of diesel concerning the gas i (in tonnes per litre).

3.1.6.4. GHG emissions from CDW management

For CDW management processes, a portion of CDW is recycled and the rest sent to landfill.

Thus, the GHG emissions associated with the recycling processes of CDW are calculated as per Eq. (5).

$$E_{r-j,i} = W_j \times \sum_{s=1}^{S} EC_{s,j} \times EF_{s,i} \quad (5)$$

where $E_{r-j,i}$ is the emission of the specific GHG i generated during the recycling process of the building material j (in tonnes); $EC_{s,j}$, energy consumption from the energy source s involved in the recycling processes of the building material j (in GJ per tonne); S, the number of energy sources; W_j, the weight of the building material j (in tonnes); and $EF_{s,i}$, the emission factor of the energy source s concerning the gas i (in tonnes per GJ).

Concerning the estimation of CH_4 emissions from landfilling ($E_{l,methane}$), the calculation method proposed by the IPCC (2006), called First Order Decay (FOD) method, is employed. This method assumes that degradable organic carbon waste decays slowly throughout a few decades, during which CH_4 and CO_2 are formed (IPCC, 2006).

3.1.6.5. GHG emissions from the entire life cycle

Thus, the GHG emissions associated with the entire life cycle of a building are calculated per Eq. (6).

$$E_{tot} = \sum_{i=1}^{I} \left(E_{j,i} + E_{s,i} + E_{t-j,i} + E_{r-j,i}\right) \times GWP_i + E_{l,methane} \times 28 \quad (6)$$

where E_{tot} is the total emissions (in t CO_2eq.); and I, the number of GHG types.

3.2. LCI analysis

3.2.1. Data collection

Collecting the data on material and energy consumption is certainly the most time-consuming part of carrying out an LCI analysis. The data used in this paper were retrieved from different sources. Estimations of amounts of materials and energy consumption from construction site equipment are based on the 13th edition of TCPO (2012). Some emission factors and energy inputs required for the extraction, production, and transportation of materials were mainly acquired from Costa (2012), which in turn is based on the data obtained from the Brazilian Energy Balance (Brazil, 2012). For other emission factors and input data concerning the landfill emissions, the Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) from the Intergovernmental Panel on Climate Change (IPCC) was used.

3.2.2. Relating data to the life cycle of the housing complex

Table 4 shows the material and energy flows associated with the housing complex's life cycle.

4. Results and discussion

4.1. LCIA

In general, CO_2 emissions dominate the whole life cycle of the housing complex, except CH_4 emissions from the landfill during the end-of-life stage. Total GHG emissions estimated over its 50-year lifetime corresponds to 282.62 tCO_2eq., which can be expressed as 20.19 $kgCO_2eq./m^2/year$.

4.1.1. Building materials contribution

Fig. 5a shows the relative contribution of upstream processes for building materials production to GHG emissions generated during the housing complex's life cycle. The highlight is the cement, which dominates the GHG emissions from extraction and production (19.16 tCO_2eq.). It is followed by wooden materials (17.94 tCO_2eq.) and ceramics (11.68 tCO_2eq.). Around 54% of cement emissions come from the calcination of limestone, 44.8% from the combustion of fossil fuels, and only 1.2% from the use of other energy sources during the clinker production.

4.1.2. Direct energy consumption contribution

Building operation dominates GHG emissions from energy consumption (119.47 tCO_2eq.). In this process, natural gas consumption accounts for about 66% of GHG emissions, while electricity consumption accounts for about 34% over the 50-year useful life of the housing complex (Fig. 5b).

4.1.3. Transportation contribution

Transportation of building materials is responsible for 3% (8.50 tCO_2eq.) of total GHG emissions associated with the housing complex's life cycle. Displacements between industrial plants and distribution centres account for most of these emissions (6.15 tCO_2eq.). Among all building materials considered, transportation of sand is responsible for 31% (2.61 tCO_2eq.) of total GHG emissions from transport, followed by transportation of gravel, with 21% (1.83 tCO_2eq.), and wood, with 12% (0.99 tCO_2eq.) (Fig. 6a).

4.1.4. Life cycle stages contribution

The housing complex's use stage overshadows the rest of its life cycle, accounting for 56% of total GHG emissions. Pre-use and end-of-life stages account for 30% and 14%, respectively (Fig. 6b). Besides, pre-use and end-of-life stages are dominated by indirect GHG emissions, while the use stage is dominated by direct GHG emissions (Fig. 7a). Fig. 7b shows the GHG emissions from the deposition of building materials in a landfill. The three peaks in the graph represent absolute emissions generated in pre-use, use, and end-of-life stages that reduce slowly throughout a few decades (FOD method). It is possible to verify that the accumulated emissions in terms of CO_2eq. over 225 years (when emissions become stable) are for each of these three stages 3.95, 23.20, and 23.18, respectively – resulting in total emission of 50.34 tCO_2eq. GHG emissions from the recycling of CDW were quantified at 18.76 tCO_2eq.

4.2. Interpretation

Using the carbon emission per unit of area method, the GHG emissions from all life cycle stages of the housing complex over its 50-year lifetime can be expressed as 1,009.34 $kgCO_2eq./m^2$/50-year or 20.19 $kgCO_2eq./m^2/year$, and then compared with different buildings. These values conform with what has been found by most previous works that evaluated the buildings-related GHG emissions from a life cycle perspective (Bribián et al., 2009; Evangelista et al., 2018; Säynäjoki et al., 2011; Schwartz et al., 2018). Considering the similarity of building types, the result obtained in the present study is highly in line with the GHG emission intensity (19-23 $kgCO_2eq./m^2/year$) of multi-family dwelling (social interest housing) and single-family dwelling (low standard) in another Brazilian study which was conducted by Evangelista et al. (2018). By analysing different studies worldwide, Schwartz et al. (2018) indicate that new residential buildings' carbon footprint is 1,162 $kgCO_2/m^2$/50-year on average, considering 19 different countries. In Asdrubali et al. (2013), the GHG emissions from the whole life cycle of a multi-dwelling building in Italy are 53 $kgCO_2eq./m^2/year$. At the same time, Motuziene et al. (2015) state that these emissions can reach 2,793 $kgCO_2eq./m^2$ for a single-family house built using masonry materials throughout its 100 years service life in Lithuania. Note that some of the reasons behind the discrepancies between the results include the share of renewable energy sources within the national electricity mix, the heating and cooling requirements depending on the climate conditions and the buildings' service life (Sadeghifam et al., 2015).

Table 4. Quantification of inputs and outputs from the life cycle of the housing complex

Inputs/Outputs	*Unit*	*Stages*		
		Pre-use	*Use*	*End-of-life*
Materials inputs				
Steel	kg	5.343	44	-
Sand	kg	127.517	709	-
Adhesive mortar	kg	2.384	2.384	-
Gravel	kg	89.812	-	-
Hydraulic lime	kg	5.468	81	-
Ceramics	kg	53.149	17.642	-
Cement	kg	28.926	81	-
Gypsum	kg	1.922	-	-
Peroba rosa wood	kg	4.198	4.198	-
Paraná pine wood (door and window frames)	kg	1.584	1.584	-
Paraná pine wood (formwork system)	kg	985	-	-
Direct energy inputs				
Electricity	kWh	1.756	769.200	-
Natural gas	m^3	-	30.000	-
CDW management				
Recycling	kg	7.771	8.844	75.806
Landfilling	kg	22.026	20.254	216.139

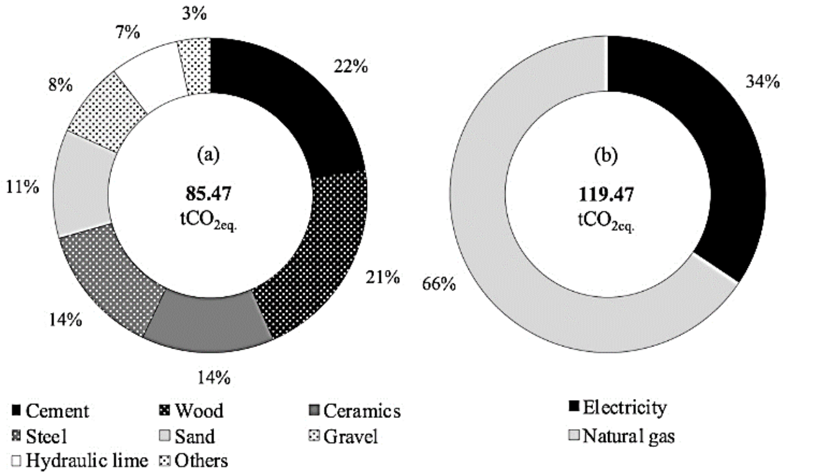

Fig. 5. GHG emissions from the extraction and production of materials (a) and from direct energy consumption (b)

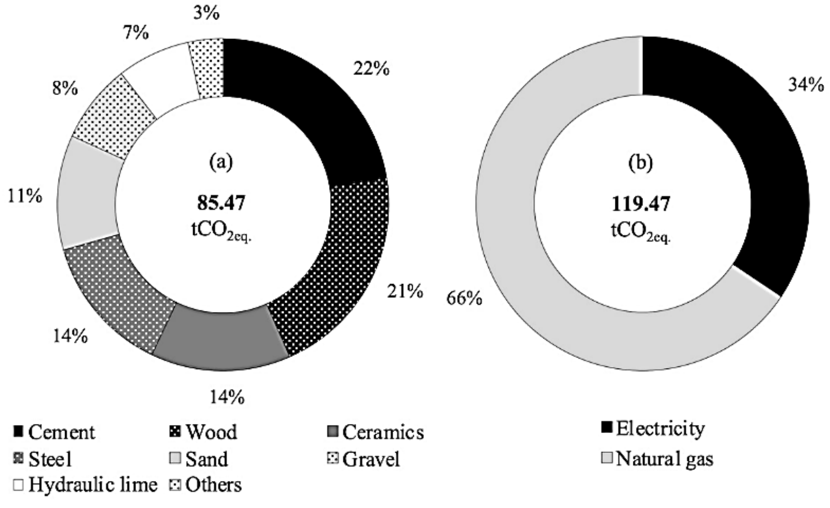

Fig. 6. GHG emissions from transportation and distribution of materials (a) and each life cycle stage of the housing complex (b)

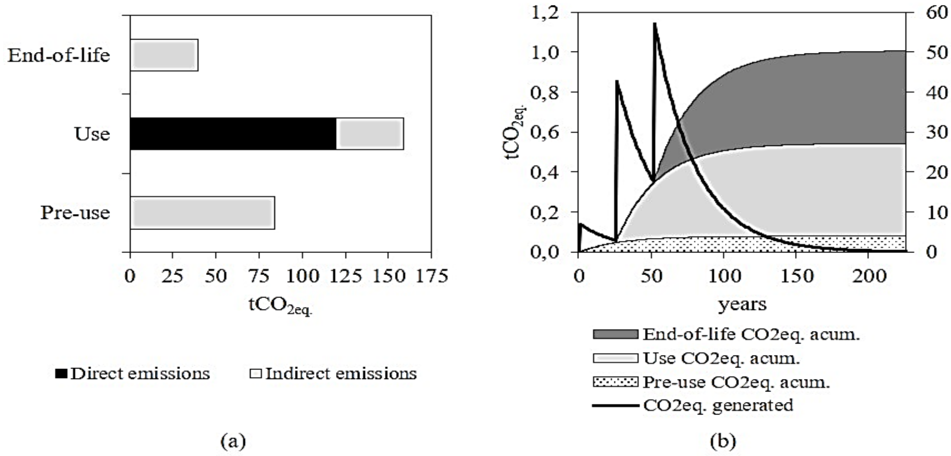

Fig. 7. Direct and indirect GHG emissions from each life cycle stage of the housing complex (a) and GHG emissions from the landfilling of CDW (b)

Despite the continuous effort to reduce the operating energy in buildings being consistent with current energy policies (Hanandeh, 2015; Sadeghifam et al., 2015), life cycle-based decisions in the earlier stages of the building design have a role to play in improving the sustainability performance of buildings during the transition towards sustainable development. As a result, embodied impacts have gained importance (Blengini and Carlo, 2010; Goldstein and Rasmussen, 2018; Lippiatt, 2007; Vares et al., 2019). In this context, our findings are supported by other studies that reveal that the highest part of embodied impacts of buildings is related to the extraction and production of building materials (Vares et al., 2019). This is particularly interesting for Brazil, where a high level of informality is observed in the construction sector and environmentally friendly products are often labeled as 'high-cost products.' Consequently, the use of 'green' building materials has not been a priority during the design and construction stages in the country. In fact, the costs and performance and aesthetic characteristics are the key factors in the building material selection (Borja et al., 2019; Pacheco-Torgal et al., 2014).

Given this situation, it is possible to indicate mitigation measures related to the cement industry since cement was the most GHG emissions-intensive building material (19.16 tCO_2eq.; or 22% among the building materials considered in this study). Among several available measures to reduce CO_2 emissions in the short-term, it is interesting to note that using more efficient energy sources in industrial processes, replacing fossil-based energy with renewable one, and designing building materials considering their impacts on the environment have the potential to decrease the carbon intensity of buildings in a cost-effective manner (Ajayia et al., 2019; Säynäjoki et al., 2011).

Production of blended cement seems a promising option to reduce both fuel-and process-related CO_2 emissions (Fairbairn et al., 2012; Pacheco-Torgal et al., 2014; Säynäjoki et al., 2011). In this process, a portion of the clinker is replaced with industrial by-products with pozzolanic properties, such as blast furnace slag and coal fly ash (Pacheco-Torgal et al., 2014). The potential for CO_2 emissions reduction estimations through this measure is from 5% to 20% (Säynäjoki et al., 2011). In the Brazilian context, this mitigation measure is especially relevant as it is expected to reach a clinker/cement ratio of around 0.52 by 2050, which would reduce GHG emissions by approximately 69% within the Brazilian construction sector, based on 2014 levels (Brazil, 2015). Simultaneously, reductions obtained from the improved efficiency in cement kilns depend essentially on the technology employed but can reach 8%. Another possibility consists of increasing the use of renewable energy sources. Replacing 30% of thermal energy with alternative energy sources can reduce CO_2 emissions by 4% (Ajayia et al., 2019).

5. Conclusions

This paper presented a life cycle-based analysis to assess the GHG emissions from a housing complex located in Brazil. Firstly, our findings showed that CO_2 dominated the total GHG emissions, except CH_4 emissions from landfills. Within the scope of our analysis, CH_4 emissions from other stages can be unconsidered, as well as N_2O emissions from all stages of the life cycle. Total GHG emissions generated over the housing complex's life cycle were 282.62 t CO_2eq., which can also be expressed as 1,009.34 kg CO_2eq./m^2/50-year or 20.19 kgCO_2eq./m^2/year.

Use stage was responsible for the largest part of GHG emissions (56%), followed by pre-use (30%) and end-of-life stages (14%). Despite the ongoing efforts to reduce the operating energy in buildings, embodied impacts have been gaining importance in modern environmental policies. Not surprisingly, indirect emissions accounted for more than half of total GHG emissions (57%), mainly driven by emissions from building materials (85.47 tCO_2eq.; or 30%). Since cement was the most GHG emissions-intensive building material (19.16 tCO_2eq.; or 22% among the building materials considered in our analysis), the greatest opportunity for reducing GHG emissions seems to be the implementation of mitigation measures along with cement industry processes. These results can also be significant for the Brazilian context as the environmental properties of building materials have not traditionally been a priority during the design or construction of a residential building in the country. Our results may vary substantially since our analysis was based on several specific factors, such as the source of materials, national energy matrix, industrial processes, transport distances, material quality and durability, and waste final disposal scenario.

This paper provides subsidies for improving the LCA usefulness as it contributes to the mitigation of the lack of datasets that reflect the Brazilian context. It can also be a motivating first contact with the life cycle approach for decision-makers, researchers, and other interested parties seeking to lower the environmental impacts associated with the buildings in Brazil.

Finally, the main limitation of this paper is that it focuses merely on GHG emissions. From a sustainable perspective, a more holistic impact assessment of the building's life cycle would consider not only other environmental issues but also economic and social issues. With this in mind, this work has been expanding to take into account other environmental problems and encompass the social and economic pillars of sustainability.

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