Life cycle carbon emissions inventory of brick masonry and light steel framing houses in Brasilia: proposal of design guidelines for low-carbon social housing

Inventário de emissões de carbono no ciclo de vida de habitações de alvenaria e light steel framing *em Brasília: proposição de diretrizes de projeto para habitações de interesse social de baixo carbono*

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Abstract

This study evaluated the CO_{2eq} emissions during the life cycle of two social housing projects in the city of Brasilia. A house of ceramic brick masonry was compared to a light steel framing one. The life cycle carbon emissions assessment ($LCCO_2A$) with a cradle-to-grave approach was used. The relation between the thermal performance of the wall systems and CO_{2eq} emissions in the operational phase of the houses were evaluated using the DesignBuilder software. In addition, six scenarios composed of three CO_{2eq} emission factors from the Brazilian electrical grid and two schedules of occupation of houses (full and part time) were evaluated. The brick masonry house presented less CO_{2eq} emissions than the light steel framing one. For both houses, the operational phase was the most significant regarding the total CO_{2eq} emissions (50% to 70%), followed by the construction (20% to 30%), maintenance (11% to 20%) and end-of-life (lower than 1%) phases. The results also showed the importance of considering different CO_{2eq} emission factors for the Brazilian context in the operational phase. Finally, based on the results obtained, design guidelines for low carbon social housing were proposed.

Keywords: $LCCO_2A$. Social housing. Thermal performance. Design guidelines.

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Resumo

Este estudo avaliou as emissões de CO_{2eq} no ciclo de vida de duas habitações de interesse social, uma de alvenaria de blocos cerâmicos e outra de light steel framing. *Como metodologia foi utilizada a Avaliação do Ciclo de Vida de Emissões de Carbono (ACVCO₂), com o escopo do berço ao túmulo. Foi avaliada a relação entre o desempenho térmico dos sistemas de vedação vertical e emissões de CO_{2eq} na etapa operacional das habitações utilizando o software DesignBuilder. Foram avaliados seis cenários da etapa operacional, compostos de três fatores de emissões de CO_{2eq} da matriz elétrica brasileira e duas agendas de ocupação das habitações. A habitação de alvenaria cerâmica apresentou menores emissões de CO_{2eq}, e para ambas as habitações a etapa operacional se mostrou a mais significativa (50% a 70%), seguida da construção (20% a 30%), manutenção (11% a 20%) e fim de vida (menor que 1%). Os resultados mostraram a importância de se considerarem diferentes fatores de emissões de CO_{2eq} na etapa operacional. Ao final, com base nos resultados obtidos, foram propostas diretrizes de projeto para habitações de interesse social de baixo carbono.*

Palavras-chave: ACVCO₂. Habitações de interesse social. Desempenho térmico. Diretrizes de projeto.

Introduction

In 2010, buildings accounted for 32% of the total global final energy use and 19% of energy-related greenhouse gas (GHG) emissions (LUCON *et al.*, 2014). The Brazilian residential buildings were responsible for 21% of the country's electricity consumption in 2015 (MINISTÉRIO…, 2016).

Brazil is a developing economy, a factor that influences the building sector. There is a housing deficit in the country and to overcome this problem, the Brazilian government has developed housing programs in recent decades such as "My house, My Life" (Minha Casa, Minha Vida) (PAULSEN; SPOSTO, 2013). Despite failures and criticism mainly related to the quality of the houses built, this program was responsible for the construction of thousands of new homes for people in need, thus alleviating the housing deficit in the country.

These social housing programs mainly used the brick masonry system. However, new building systems, which may be more rational and productive, are being considered, such as precast and prefabricated concrete, concrete walls and light steel framing. The latter has been imported from the USA and its use is becoming widespread in the country, due to higher productivity and the dry construction process (LIMA, 2016).

Nevertheless, it is necessary to define some environmental criteria, such as embodied energy and CO_2 emissions, water consumption, waste and others, to help architects and engineers to specify more environmental sustainable systems (CARVALHO; SPOSTO, 2012).

According to Cabeza *et al.* (2014) and Chau, Leung and Ng (2015), the life cycle assessment (LCA), the life cycle energy assessment (LCEA) and the life cycle carbon emissions assessment (LCCO$_2$A) are some of the available and internationally widespread methodologies for environmental assessment in the building sector.

The life cycle assessment (LCA) evaluates all the resource inputs, including energy, water and material consumption, and environmental loads, including CO_2 emissions, as well as liquid and solid wastes of a product or a process (INTERNATIONAL…, 2006). However, it has been observed that most of the research about LCA applied to buildings has focused on energy consumption and CO_2 emissions. Within this context, more specific tools such as life cycle energy assessment (LCEA) and life cycle carbon emissions assessment (LCCO$_2$A) were developed.

LCEA and LCCO$_2$A are simplified versions of LCA. While the first one focuses only on the evaluation of energy inputs, the second focuses on CO_2 emissions in different phases of a building's life cycle (CHAU; LEUNG; NG, 2015).

In Brazil, most studies of LCCO$_2$A focus on building materials. Campos, Punhagui and John (2011) estimated the CO2 emissions from the transportation of Amazon wood and evaluated the reduction of net carbon stock, due to this phase in the production process. Passuelo *et al.* (2014) evaluated the carbon footprint of an alternative laboratory-produced clinker. Saade *et al.* (2014) proposed a set of lifecycle-based indicators to describe eco-efficient building materials, presenting an important environmental database for Brazilian building materials, including CO$_2$eq emissions. Borges *et al.* (2014) compared Portland cement and geopolymer concretes obtained from the alkaline activation of aluminosilicates. Santoro and Kripka (2016) evaluated CO_2 emissions of concrete production, considering the material (binder, coarse aggregates, fine aggregates and steel) extraction and production stages used in the state of Rio Grande do Sul.

Paulsen and Sposto (2013) evaluated the energy consumption (embodied and operational energy) using the LCEA, during the life cycle of a typical social house in Brazil. Souza *et al.* (2016) used the LCA to compare three kinds of wall systems, made of concrete bricks, ceramic bricks and cast-in-place concrete. Atmaca and Atmaca (2015) applied the LCEA and LCCO$_2$A to compare two residential buildings in Turkey, one located in a rural area and the other, in the city. Cabeza *et al.* (2014) and Chau, Leung and Ng (2015) revised the state of the art related to the LCA, LCEA and LCCO$_2$A applied to the building sector.

Caldas (2016) and Caldas and Sposto (2016) compared one brick masonry and one light steel framing house in terms of thermal performance and embodied energy in Brasilia using the LCEA. The brick masonry house presented a better thermal performance and lower energy consumption during its life cycle. The present paper intends to continue these studies, though focusing on carbon emissions and analyzing different scenarios for the operational phase.

Although there are some studies in Brazil quantifying the energy consumption in a building's life cycle, there are fewer studies related to carbon emissions assessment, considering thermal performance and taking a cradle-to-grave approach.

Thus, through the LCCO$_2$A methodology, the aim of this study is to evaluate the CO$_2$eq emissions during the life cycle of two social housing projects

located in Brasília. Two different wall systems were compared: Brazilian conventional ceramic brick masonry and light steel framing, considering the buildings' entire life cycle, called cradle-to-grave in literature (construction, use and end-of-life phases).

Two important and innovative aims of this study were:

(a) the consideration of different operational phase scenarios, in terms of schedules of occupation of the buildings and different CO_2eq emission factors from the Brazilian electricity matrix; and

(b) the proposal of some design guidelines for low carbon social housing based on the quantitative results of the $LCCO_2A$ of buildings.

Methodology

Functional unit, scope and description of the building

The Functional unit (FU) for this study is a house located in Brasília – DF, with 4 residents (2 adults and 2 children), an internal floor area of 46 m² and a 50-year lifespan (minimum value stipulated in the NBR 15575-1 (ABNT, 2013)). Brasília is situated in the Brazilian Bioclimatic Zone number 4 (NBR 15220-3 (ABNT, 2005)).

The house project consists of one living room, two bedrooms, one kitchen, one bathroom and one outdoor laundry area. There are three internal doors, two external doors and five windows. The solar orientation (facing the North) was chosen according

to the worst situation related to thermal gains in the house, which was obtained in pre-simulations in the DesignBuilder. The west orientation for the bedrooms was chosen as presented in Figure 1. The foundation is not included in this study once it depends on the characteristics of the soil. Paulsen and Sposto (2013) adopted the same criteria.

The Brazilian conventional wall system is ceramic brick masonry with mortar plaster and reinforced concrete columns and beams, U-value: 2.5 W/m².K. The light steel framing wall consists of galvanized steel frames with two oriented strand boards (OSB), one gypsum fiberboard in the internal area, one fiber cement board in the external area and an insulation layer of rock wool, U-value: 0.7 W/m².K, as presented in Figure 2.

Table 1 below shows the cradle-to-grave scope, which includes construction (extraction, processing of raw materials and transportation of the building materials from factories to the site location), operation of the building, maintenance and end-of-life. The results are presented in terms of carbon dioxide equivalent (CO_{2eq})[1].

Construction phase analysis

The CO_{2eq} emissions in the construction phase were taken from the literature. For the light steel framing, Environmental Product Declarations (EPDs) were used. The waste of building materials during the construction process was considered. The construction working process, mainly performed manually, was not factored in in this study.

Figure 1 - **DesignBuilder model of the case study**

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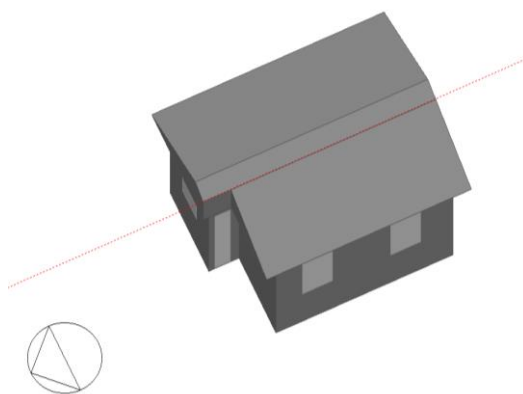
[1]For the CO_{2eq} the following global warming potentials (GWP) were considered, according to IPCC (INTERGOVERNMENTAL…, 2013): 1 for CO_2, 28 for CH_4 and 265 for N_2O.

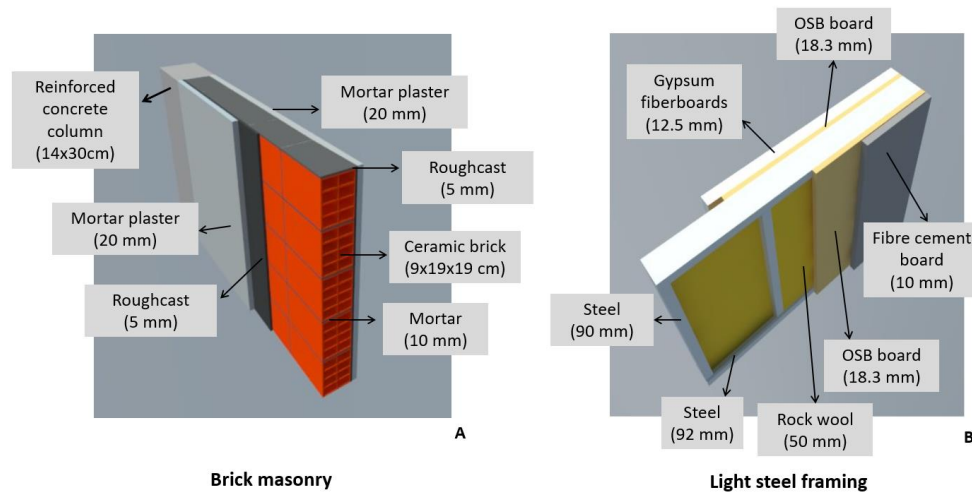Figure 2 - **Comparison between the two wall systems**

Brick masonry

Light steel framing

Table 1 - **Phases in the life cycle of the house**

Phases	Stages	Symbols	Description
Construction (ECO$_2$C)	Extraction, processing of raw materials	ECO$_2$E	CO$_{2eq}$ emissions of building materials production
	Transport	ECO$_2$T	CO$_{2eq}$ emissions of transport from factories to site location
Use (ECO$_2$U)	Operational	ECO$_2$O	CO$_{2eq}$ emissions of electrical equipment and for cooking
	Maintenance	ECO$_2$M	CO$_{2eq}$ emissions of materials used in maintenance
End-of-life (ECO$_2$EL)	Demolition/Deconstruction	ECO$_2$D	CO$_{2eq}$ emissions of demolition or deconstruction of house
	Waste Transport	ECO$_2$Tw	CO$_{2eq}$ emissions of transport of waste from site location to landfill
	Waste disposal in landfill	ECO$_2$L	CO$_{2eq}$ emissions of activities for waste disposal in landfill
Whole life cycle	All stages	ECO$_2$TOT	Sum of CO$_{2eq}$ emissions of all stages of the house life cycle

In Brazil, building materials are commonly transported by truck. In this case, the value of fuel consumption of 0.017 L diesel/t.km was adopted, as presented by Campos, Punhagui and John (2011). The full truckloads on the outbound route (from the factory location to the construction site) and half of the truckloads on the inbound route were recorded, therefore multiplied by a factor of 1.5. According to IPCC (INTERGOVERNMENTAL…, 2006) and MMA (MINISTÉRIO…, 2013), one liter of diesel is equivalent to 2.63 kg CO$_{2eq}$, resulting, in the end, in a transport coefficient of 0.067 kgCO$_2$/t.km. The Google Maps app was used to calculate the transport distances, considering the shortest distance between the construction site and the building material producers (Table 2).

Use phase analysis

Operational stage

The operational energy and CO$_{2eq}$ emissions were divided into three parts: electricity used for equipment, liquefied petroleum gas (LPG) used for cooking and energy used for air conditioning (calculated in relation to the thermal performance of the buildings).

For the cooling simulation, the U-values used for brick masonry and light steel framing walls were 2.5 W/m².K and 0.7 W/m².K, respectively. For windows, the U-value 5.6 W/m².K was used (6 mm glass). Air conditioning appliances (split) were adopted for rooms in which people normally spend more time, such as the living room and the bedrooms. The cooling set point was fixed at 24.3

°C for these areas, according to the comfort zone of the city of Brasilia, defined by the neutral temperature equation presented by Pereira and Assis (2010). The machine efficiency (CoP) adopted was 2.8, a common value for this kind of houses in Brazil. Part and full time schedules of occupation for the living room and bedrooms were adopted to evaluate the minimum and the maximum potential energy consumption due to the air conditioning appliances. The part-time schedule adopted was from 5 p.m. to 12 a.m. for the living room, and 12 a.m. to 7 p.m. for the bedrooms.

EnergyPlus through DesignBuilder was used to evaluate the impact of variations of the external and internal walls on annual energy use and CO_{2eq} emissions of the building by dynamic thermal and energy simulation. After the simulation, the energy consumption for other electrical equipment (electric shower, refrigerator, TV, lighting, etc.) was 2414.17 kWh/year.

The results found for air conditioning energy consumption were:

(a) brick masonry house with part- time schedules of occupation: 768.21 kWh/year;

(b) brick masonry house with full-time schedules of occupation: 2228.78 kWh/year;

(c) light steel framing house with part-time schedules of occupation: 1271.05 kWh/year; and

(d) light steel framing house with full-time schedules of occupation: 3219.14 kWh/year.

Table 2 - Data on building materials in the studied houses (46 m²)

Building materials	Amount (kg/m²)	Embodied emissions intensity (kgCO$_{2e}$/kg)	Source	Waste (%)	Transport Distances (km)
Brick Masonry					
Ceramic brick	165.3	0.24	Saade et al. (2014)	15%	97
Mortar plaster	375.5	0.18[1]	Saade et al. (2014)	20%	29.7
Concrete	138.3	0.16[2]	Saade et al. (2014)	9%	16.8
Wood (formwork)	28.3	0.96[3]	Saade et al. (2014)	10%	75
Steel rebar	10.9	1.95	Saade et al. (2014)	10%	843
Light steel framing					
Steel structure	1	1.78	Saade et al. (2014)	10%	975
OSB board	71.2	0.96[3]	Saade et al. (2014)	15%	1298
Gypsum fiberboards	49.1	0.22	Knauf[1] (2013b)	9%	1195
Cement fiberboards	44.4	0.36	Knauf[1] (2013a)	9%	213
Rock wool	6.4	0.88	Deutsche Rockwool[1] (2012)	5%	1014
Other systems of the house					
Paint (internal and external walls)	4.9	1.99	Saade et al. (2014)	15%	224
PVC (installations)	3.6	9.85	Saade et al. (2014)	5%	165
Ceramic tile (roof)	67.1	0.13	Saade et al. (2014)	10%	337
Wood (roof)	17.2	0.11[4]	Saade et al. (2014)	4%	687
PVC (ceiling)	2.4	9.85	Saade et al. (2014)	5%	225
Cement CPII (floor)	14.2	0.66	Votorantim Cimentos (2016)	20%	30
Sand (floor)	69.2	0.01	Santoro e Kripka (2016)	20%	277
Adhesive mortar	4.9	0.99	Saade et al. (2014)	5%	30
Ceramic tile (floor)	10.9	0.24	Saade et al. (2014)	6%	740
Steel (windows and external doors)	14.4	1.95	Saade et al. (2014)	2%	214
Glass (windows)	1.6	1.00	Saade et al. (2014)	1%	214
Wood (internal doors)	8.6	0.96[3]	Saade et al. (2014)	1%	222

Note: Legenda:
[1]Only cradle-to-grave data were considered;
[2]The density of concrete was considered to be 2400 kg/m³;
[3]The density of wood was considered to be 650 kg/m³; and
[4]The density of wood was considered to be 650 kg/m³.

Three different values were used to estimate the CO_{2eq} emissions of the Brazilian electricity matrix: (1) minimum value (FCO_{2min}): 0.025 $kgCO_{2eq}$/kWh; (2) median value FCO_{2med}: 0.064 $kgCO_{2eq}$/kWh; (3) maximum value (FCO_{2max}): 0.135 $kgCO_{2eq}$/kWh, according to data collected by the Ministry of Science and Technology (*Ministério de Ciência e Tecnologia* – MCTI (MINISTÉRIO…, 2016)). As a result, there were six scenarios for the operational phase for each house:

(a) $FCO_{2\,min}$ and full- time schedule of ocupation (FCO_{2min} full);

(b) $FCO_{2\,min}$ and part- time schedule of ocupation (FCO_{2min} part);

(c) $FCO_{2\,med}$ and full- time schedule of ocupation (FCO_{2med} full);

(d) $FCO_{2\,med}$ and part- time schedule of ocupation (FCO_{2med} part);

(e) $FCO_{2\,max}$ and full- time schedule of ocupation (FCO_{2max} full); and

(f) $FCO_{2\,max}$ and part- time schedule of ocupation (FCO_{2max} part).

The energy used for cooking comes from LPG, assuming a consumption of 13 kg of LPG per month. Also, a 2.98 $kgCO_{2eq}$/kg ratio (INTERGOVERNMENTAL…, 2006) was adopted. The values of the operational stage were calculated for the stipulated 50-year lifespan of the house.

Maintenance stage

The CO_{2eq} emissions from maintenance for replacing used materials in the houses were analyzed. To calculate the maintenance intervals, data from the Brazilian building performance standard (ABNT, 2013) were used, resulting in replacement factors (RF). The same method was used by Paulsen and Sposto (2013), Atmaca and Atmaca (2015) and the other authors presented in Table 3.

The interior walls presented the largest difference when comparing the Brazilian RF and the mean value from other studies. A service life of 20 years was assumed for light steel framing and gypsum interior walls, resulting in a RF of 2.5. Whereas for the brick masonry system, a service life of 40 years for mortar covering was assumed, leading to a RF of 1.3. The transport of building materials and components used in maintenance were taken into account, adopting the same assumptions of the construction phase. The transport distance of replaced materials to landfills was assumed to be 20 kilometers from the building site during the maintenance phase. The demolition/deconstruction and disposal of these materials were allocated to the end-of-life phase. The end-of-life method is better detailed in the end-of-life phase section.

Table 3 - Replacement factor (RF) in different studies

Building component	Treolar et al. (1999)[1]	Chen et al. 2001)[1]	Keoleian et al. 2000)[1]	Scheuer et al. (2003)[1]	Chau et al. (2007)[1]	Ding (2007)[1]	Paulsen and Sposto (2013)	Atmaca and Atmaca (2015)	Mean[2]	This study[3]
Country	Australia	Hong Kong	USA	USA	Hong Kong	Australia	Brazil	Turkey	-	Brazil
Walls (Exterior)	1.1	1	-	1	1	1	1.3	1.1	1.1	1.3
Walls (Interior)	1.1	1	-	1	1	2.4	2.5	1.1	1.4	1.3-2.5
Doors	-	1.3	-	1.5	-	1.5-2	1.3	2	1.6	1.3
Windows	-	1.3	2	1.9	-	1.5	1.3	2	1.7	1.3
Roof	-	1.3	2	3.75	2.5	2.4	2.5	2	2.6	2.5
Floor	4	3	2.5	4.16	2.5	3	3.8	3	3.2	3.8
Paints	8	5	5	15	5	6-8.6	-	5	7.6	10
Ceiling	2	2	-	3.75	2.5	4	-	3	2.7	3

Note: [1]Information obtained from Atmaca and Atmaca (2015).
[2]Average value from studies.
[3]Based on NBR 15575-1 (ABNT, 2013).

End-of-life phase analysis

In the end-of-life phase, it was assumed that the building with brick masonry was demolished and the generated waste was transported to the nearest landfill, located 20 kilometers from the building site. The building with light steel framing was assumed to have been deconstructed and the assumed generated waste transported to the nearest landfill.

The end-of-life phase was divided into three stages:

(a) demolition/deconstruction;

(b) waste transport to the landfill; and

(c) waste disposal in the landfill.

Values of 0.00247 kgCO$_2$/kg were used for the demolition (ceramic brick masonry) and 0.000092 kgCO$_2$/kg for deconstruction (light steel framing), based on Pedroso (2015) primary data. For the transport to the landfill, the same emission data were used for the truck transportation of building materials. For waste disposal activities performed in the landfill, a ratio of 0.37 L of diesel per 1 tonne of waste was assumed, an average value obtained from Bovea and Powell (2016) considering that one liter of diesel is equivalent to 2.63 kg CO$_{2eq}$ (MINISTÉRIO…, 2013).

According to IAB (INSTITUTO…, 2016), currently in Brazil about 30% of all the steel produced comes from recycling. Usually, this recycled steel has already been accounted for in terms of the recycled content in steel production, using one of the approaches presented by Bergsma and Sevenster (2013). Therefore, the benefits of steel recycling in light steel framing were not considered. The only difference between steel and other materials is the third stage (3). Steel does not go to landfills; therefore it produces no emissions in this phase. Its transport distance to a recycling plant was assumed to be the same as that of other materials to a landfill.

Design guidelines for low carbon social housing

The design guidelines for low carbon social housing were given based on the quantitative results of CO$_{2eq}$ emissions during the houses' life cycle. Each phase of the life cycle was analyzed individually and, in the end, their impact in terms of total CO$_{2eq}$ emissions was verified, and the guidelines were classified according to priority (high, medium-high, medium and low). Some suggested guidelines, based on the literature, were generic or not evaluated in this study. However, some points should be addressed in future studies.

Although this paper presents a case study with some particularities, such as the evaluation of thermal performance just for the city of Brasilia, the authors believe that these guidelines could be an important contribution for continuous research in the field of low carbon buildings.

Results and discussion

Construction phase

For the construction phase, values of 0.38 tCO$_{2eq}$/m² and 0.32 tCO$_{2eq}$/m² (ECO$_2$E) were found for the brick masonry and for the light steel framing houses, respectively. Comparing the ECO$_2$E values, the difference was 16% with a lower value for the light steel framing system. A comparison of the different house systems in terms of mass and ECO$_2$E is shown in Figure 3.

Figure 3 - Share of the house systems in mass and ECO$_2$E for the construction phase

ECO$_2$E - Extraction, processing of raw materials
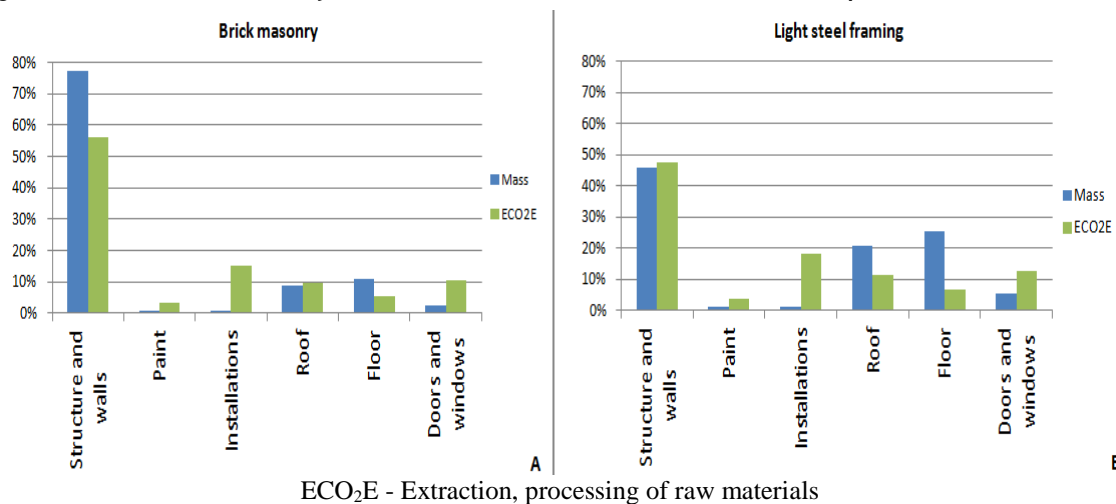
For both houses, the walls had the greatest mass (77% for brick masonry and 46% for light steel framing) and ECO_2E (56% for brick masonry and 46% for light steel framing). These results show the importance of choosing an adequate wall system in a low carbon footprint social housing design. The share of materials and components of each building's wall system in terms of mass and ECO_2E is presented in Figure 4.

The extraction and processing of raw materials were responsible for 97% of the total ECO_2E for brick masonry and 94% for light steel framing. The transportation, on the other hand, played a small role, with 3% for brick masonry and 6% for light steel framing.

For the transport phase, the mass of the light steel framing was 57% less than the mass of the brick masonry. However, the results of ECO_2T show 0.011 tCO_{2eq}/m^2 for brick masonry and 0.019 tCO_{2eq}/m^2 for light steel framing. The farther distances traveled by materials and components of light steel framing exceeded the impact of higher mass values of the brick masonry system. Therefore, to minimize the CO_{2eq} of the transport phase, it is important to specify during the design phase low mass materials and components located near the construction site.

Use phase

The use phase was composed of operational and maintenance phases. The operational CO_{2eq} emissions due to air conditioning ranged from 0.08 tCO_{2eq}/m (FCO_{2min} partial) to 0.68 tCO_{2eq}/m^2 (FCO_{2max} full) for the brick masonry house and 0.10 tCO_{2eq}/m^2 (FCO_{2min} partial) to 0.83 tCO_{2eq}/m^2 (FCO_{2max} full) for the light steel framing house. The total operational CO_{2eq} emissions (considering air conditioning, equipment and cooking) are presented in Figure 5.

The brick masonry presented a better thermal performance for the city of Brasília, due to the greater thermal capacity of the walls. According to NBR 15220-3 (ABNT, 2005) for Bioclimatic Zone 4, it is more advantageous to use heavy walls in buildings. Hence, this masonry system was expected to present the best thermal performance. However, considering the growing interest in light steel framing systems in the Federal District region, this study evaluated the impact of the thermal performance of light steel framing on life cycle carbon emissions.

The CO_{2eq} emissions due to the electricity consumption for the six scenarios, including the air conditioning use, played a small role (14-23%) in ECO_2O for the FCO_{2min} and a greater role (48-62%) for the FCO_{2max} (Figure 6).

The variation of CO_{2eq} emissions in this phase is due exclusively to the consumption of air conditioners because of the differences in thermal performance of the different facades of brick masonry and light steel frame buildings, considering the two schedules (part-time and full-time occupations) and the three CO_{2eq} factors from electricity (FCO_{2min}, FCO_{2med} and $FCO2_{max}$). The cooking process was considered the same for both buildings.

The cooking process generates more CO_{2eq} per energy. Considering FCO_{2max}, its emissions (LPG) are almost twice the emissions from the electricity used for equipment. In relation to the FCO_{2min}, the difference is almost four fold. Therefore, one important strategy to reduce operational emissions when pursuing a low carbon social housing design, especially for a FCO_{2min} scenario, is to reduce the LPG use or substitute it for a less CO_{2eq} fuel, for example, natural gas, since it emits less CO_{2eq} than the LPG.

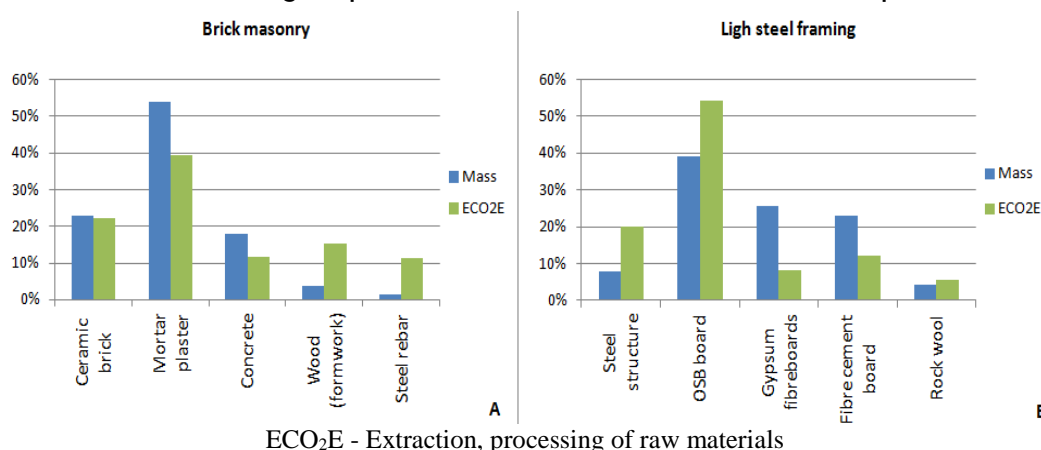Figure 4 - **Share of wall building components in mass and ECO_2E in the construction phase**

ECO_2E - Extraction, processing of raw materials

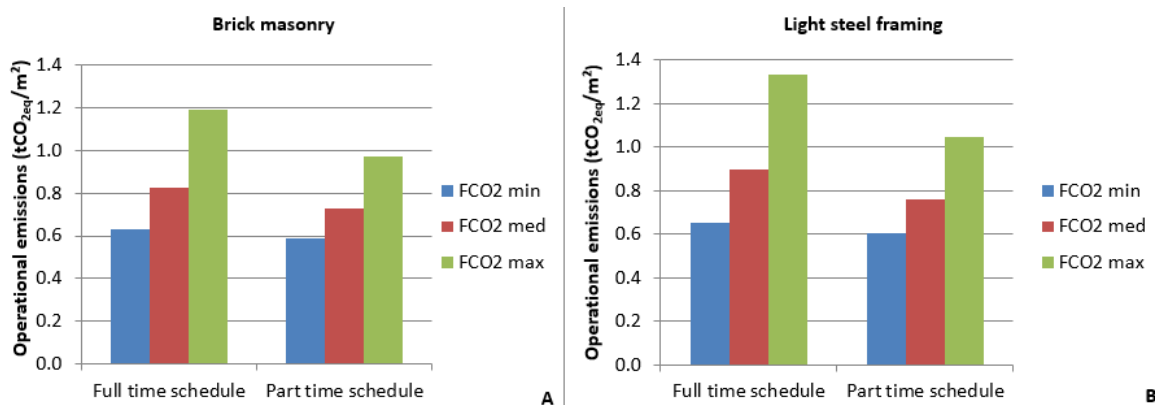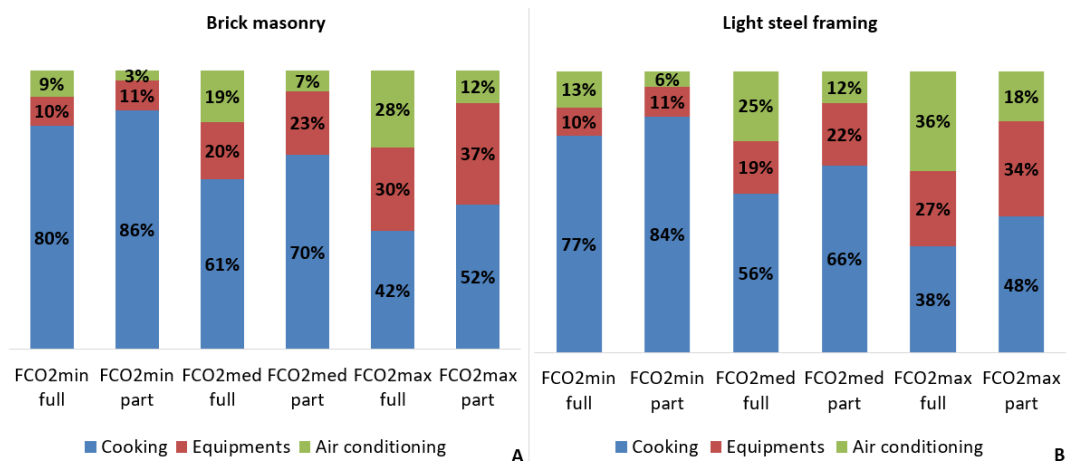Figure 5 - **Comparison of operational CO$_{2eq}$ emissions for the six scenarios**

Figure 6 - **Cooking, equipment and air conditioning share in the ECO$_2$O phase**

Regarding equipment, it is important to use pieces that consume less electricity. In Brazil, it is recommended to use label-A equipment as ranked by Procel. The electric shower accounted for the highest energy consumption and CO$_{2eq}$, representing 35.5% of emissions of electrical equipment, requiring designer's attention for low carbon social housing projects. One alternative is to install solar panels for water heating, a suggestion that is encouraged in the "*My House, My Life*" Program. Nevertheless, it is necessary to consider the embodied CO$_{2eq}$ due to material installation, replacement and end-of-life during the building's life cycle.

Concerning the maintenance phase, the results of ECO$_2$M for brick masonry and light steel were 0.19 tCO$_2$/m² and 0.24 tCO$_2$/m², respectively. The larger values for the light steel framing house are due to the gypsum board substitution (20 years), and OSB board and rock wool substitution (30 years); meanwhile, the mortar and plaster were considered to have a service life of 40 years. The mass and ECO$_2$M for the houses are compared in Figure 7.

The paint system was responsible for great CO$_{2eq}$ emissions because of the low service life considered (5 years) and the high value of embodied CO$_{2eq}$ of paints, 1.99 kgCO$_{2eq}$/kg. Therefore, to minimize the impacts of the maintenance phase it is important to specify, during the design phase, materials with low values of CO$_{2eq}$ emissions and high durability.

End-of-life phase

For the end-of-life phase, 0.0063 and 0.0024 tCO$_{2eq}$ per m² were recorded for the brick masonry and the light steel framing houses, respectively (Figure 8). The end-of-life phase considered in this study consisted of demolition (for brick masonry) and deconstruction (for light steel framing), as well as waste transportation and disposal activities in the landfill. Assuming that transport distances were the same for the brick masonry and the light steel framing houses, the difference in the results reflected the mass of the wall systems and the processes used in demolition and deconstruction.

The deconstruction process of the light steel framing resulted in less CO$_{2eq}$ than de demolition process of brick masonry. The waste transport was

influenced by the mass and distances to the landfill. In addition, the waste disposal was influenced by the mass of waste. Therefore, in order to decrease carbon emissions of the end-of-life phase, it is important to prioritize a deconstruction process over demolition, have material wastes with lower masses and choose shorter distances to disposal, reuse or recycling plants from the building location.

Overall life cycle balance

The results of ECO_2TOT for brick masonry and light steel framing houses for the six scenarios are presented in Figure 9.

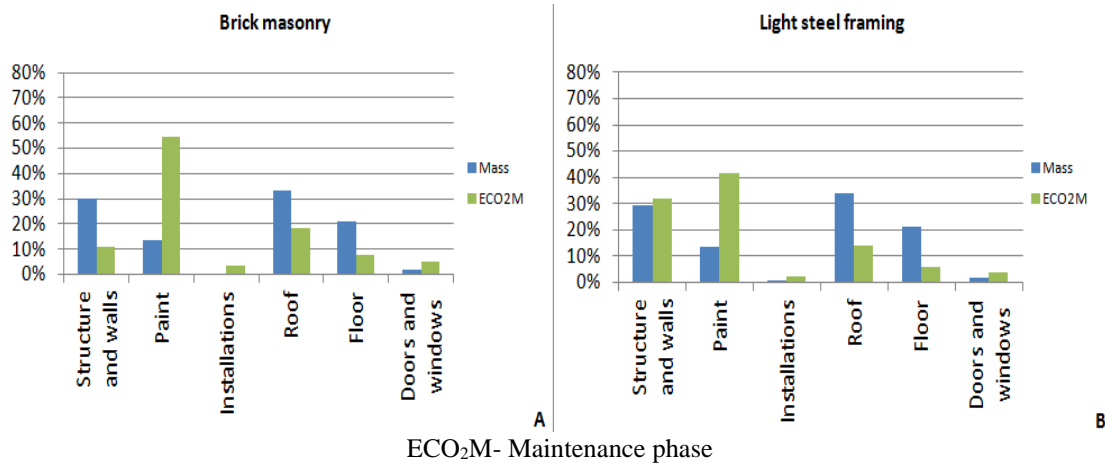**Figure 7 - Share of the house systems in mass and ECO₂M for maintenance stage**

ECO₂M- Maintenance phase

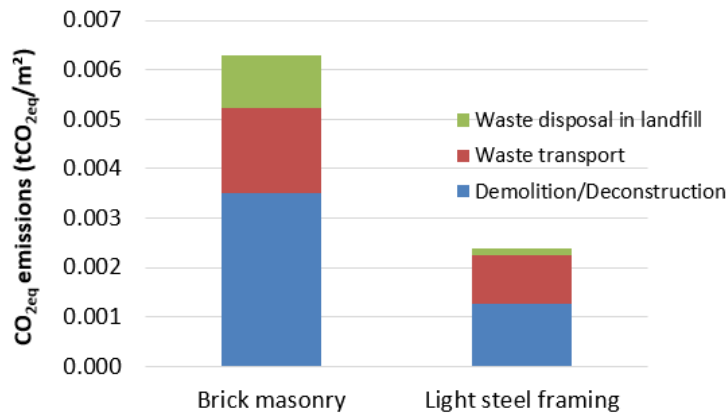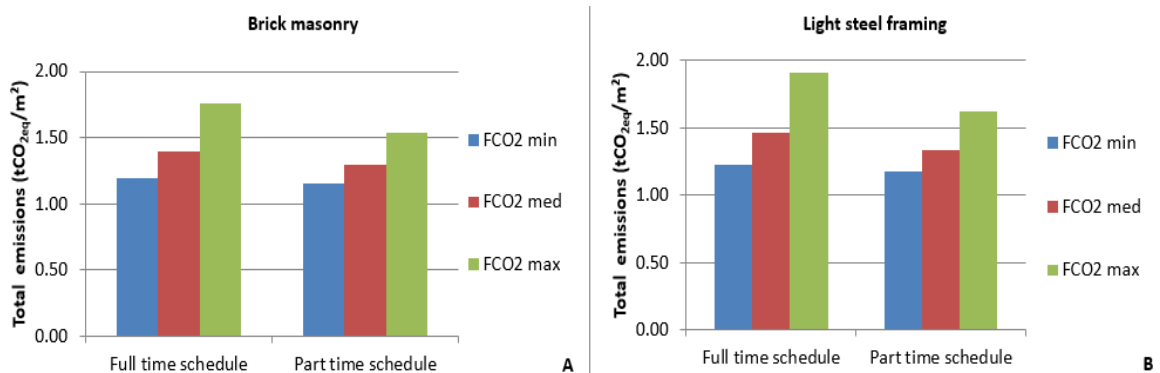**Figure 8 - Comparison of end-of-life CO₂eq (ECO₂EL) emissions**

Figure 9 - Total life cycle CO₂eq emissions assessment

The light steel framing house presented larger values of total CO_{2eq} emissions (ECO$_2$TOT) than the brick masonry house in all scenarios. The brick masonry house presented values ranging from 1.16 tCO_{2eq}/m^2 to 1.76 tCO_{2eq}/m^2 and the light steel framing presented values ranging from 1.17 tCO_{2eq}/m^2 to 1.91 tCO_{2eq}/m^2.

The biggest difference between light steel framing and brick masonry houses (8%) was seen in the full time schedule using the FCO_{2max}. In this sense, the choice of FCO_2 for electricity in this study and in the Brazilian context was an important and critical factor. This is because depending on the FCO_2 used

there is an increase or decrease in the thermal performance impact on the life cycle carbon emissions.

In Figures 10 and 11, the life cycle carbon emissions for brick masonry and light steel framing houses are presented over time. The black arrows indicate the points on the graph that represent the maintenance phase due to the replacement of materials and components.

The share of each phase in the whole life cycle of the houses for the six scenarios is shown in Figure 12.

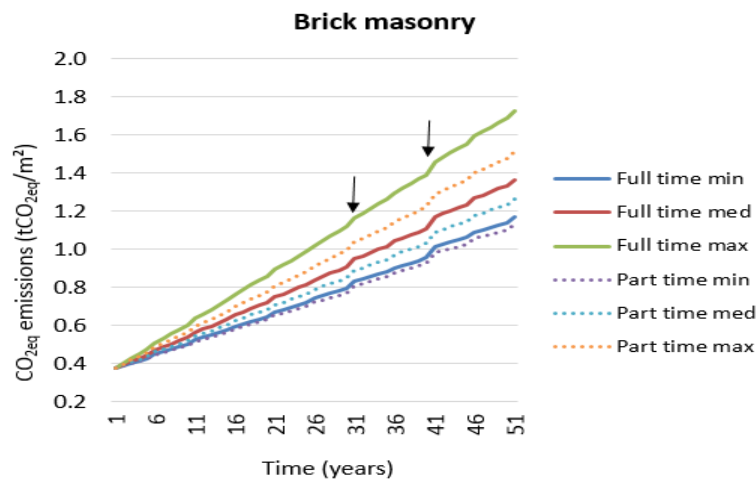Figure 10 - **Life cycle CO_{2eq} emissions over time for ceramic brick masonry house**

Figure 11 - **Life cycle CO_{2eq} emissions over time for light steel framing house**
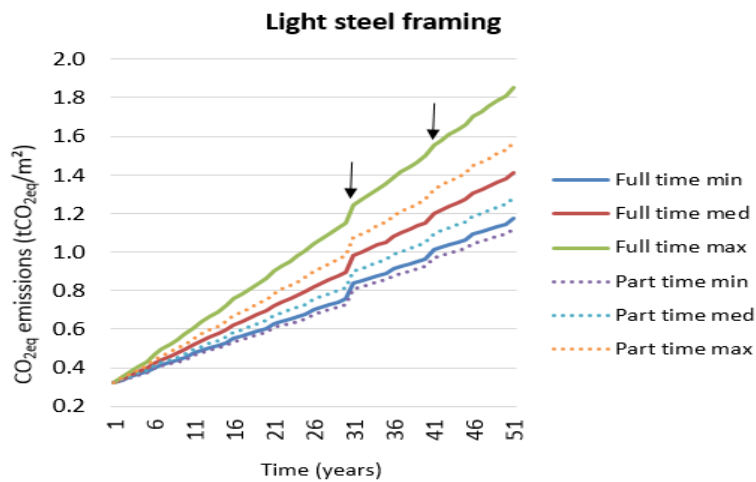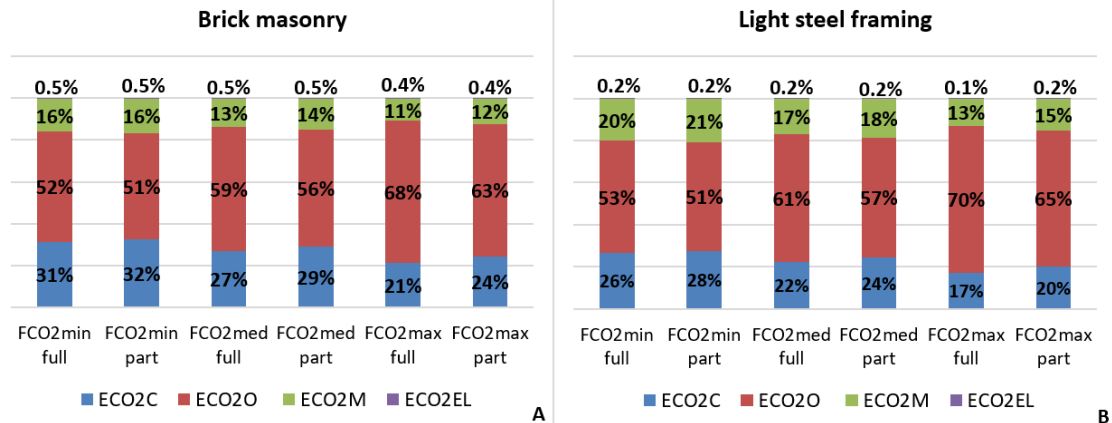
Figure 12 - **Share of each phase in the life cycle carbon emissions assessment**

ECO$_2$C– Construction phase. ECO$_2$O- Operational phase. ECO$_2$M- Maintenance phase. ECO$_2$EL- End-of-life phase

The CO_{2eq} emissions of the operational phase accounted for the highest share of the total building's life cycle, varying from 50 to 70%. In the construction phase, it varied from 20 to 30%, in the maintenance phase, from 11 to 20%, and in the end-of-life, it was lower than 1%. It is very important to know which phase has a bigger impact on the carbon life cycle of a building, indicating what the designers should give more attention to during the design stage.

Design guidelines for low carbon social housing

Finally, based on the results obtained in this study, design guidelines for low carbon social housing were developed (Table 4), as a way to guide designers and builders.

There are different ways for designers to reduce the carbon footprint of a social housing project, as presented in Table 4. However, it is important to define the critical and priority items that result in greater and more effective CO_{2eq} reduction. In this sense, the high ones (in red) deserve a greater attention from designers.

Although not evaluated in this study, bioclimatic architecture principles are very important to consider in the design phase. Features such as crossed ventilation, adequate shading and vegetation, correct openings for heated air outlet, natural lighting, adequate solar orientation and others can help minimize buildings' energy consumption. The use of these strategies related to CO_{2eq} of buildings could be evaluated in future research studies.

Conclusions

This study used the LCCO$_2$A to investigate CO_{2eq} emissions during the life cycle of two typical social house projects in Brasilia, Brazil. The variables of the study were the external and internal wall systems of the houses, with other parts remaining unchanged. A brick masonry house was compared with a light steel framing system, an industrialized system starting to gain popularity in the country.

The assessment was conducted from a cradle-to-grave perspective, including the construction, use (operation and maintenance) and end-of-life phases. The CO_{2eq} emissions from the construction phase were 0.38 tCO$_{2eq}$/m² for the brick masonry house and 0.32 tCO$_{2eq}$/m² for the light steel framing house. For the operational phase, the emissions varied from 0.59 to 1.19 tCO$_{2eq}$/m² for the brick masonry house, and 0.61 to 1.33 tCO$_{2eq}$/m² for the light steel framing house, corresponding to 50-70% of the total life cycle emissions. The emissions due to maintenance were 0.19 tCO$_{2eq}$/m² for the brick masonry, and 0.24 tCO$_{2eq}$/m² for the light steel framing. The emissions from the end-of-life phase were lower than 1% for both houses.

Comparing the different systems of the houses (walls, roof, floor, painting and installations), the wall systems presented the biggest share in terms of mass and CO_{2eq} emissions for both houses. The paint system played the biggest role in terms of CO_{2eq} emissions in the maintenance phase.

The brick masonry house presented less total CO_{2eq} emissions than the light steel framing house. The difference between the total emission values varied from 2% to 8%. This indicates that the light steel framing system for the city of Brasilia would not be a recommendable alternative in terms of CO_{2eq} emissions for the kind of buildings evaluated in this study.

Table 4 - **Design guidelines for low carbon social housing**

Phases	Stages	Design guidelines	Priority
Construction	Extraction, processing of raw materials	Specification of materials, components and systems with low values of embodied CO_{2eq} emissions and adequate thermal performance according to the location of the building. The wall system was responsible for a great share of mass and CO_{2eq} emissions in this phase, thus deserving special attention.	High
	Transport	Specification of materials, components and systems with lower mass (it is important not to forget the thermal performance) and located near the construction site.	Low
Use	Operational	Electrical equipment (no air conditioning): use of efficient equipment that consumes less electricity. Use of label-A equipment as ranked by Procel is recommended. The electric shower was the equipment that consumed the greatest share of electricity in social housing. Therefore, the installation of solar panels to heat water could be an option. The embodied carbon of materials and components and end-of-life of solar panels must be accounted for in the analysis. In a high FCO_{2eq} scenario for the Brazilian electrical matrix, this phase becomes more important.	Medium-High
		Cooking: using natural gas instead of LPG for cooking could be a good alternative to reduce CO_{2eq} emissions of buildings.	High
		Air conditioning: the specification of building systems with appropriate thermal performance to the building location is important because it will result in lower energy consumption by artificially cooling of the building. This will vary depending on the construction system adopted, location and climate zones. In a high FCO_{2eq} scenario for the Brazilian electrical matrix, this phase becomes more important.	Medium-High
	Maintenance	Specification of materials, components and systems with higher service life. Bear in mind the correct maintenance of the systems in order to extend service life and avoid total replacement of the given material, component or system.	Medium
End-of-life	Deconstruction/Demolition	Specification of systems that can be deconstructed or removed instead of being demolished.	Low
	Waste transportation	Specification of building systems with lower mass and choice of disposal sites (landfill, recycling plant, incineration facility, etc.) near the building location.	Low
	Waste disposal	Specification of building systems with lower mass to decrease diesel consumption in disposal activities.	Low

The results also showed the importance of considering different CO_{2eq} emission factors in the Brazilian context in the operational phase. Finally, based on the results obtained, design guidelines for low carbon social housing were proposed.

It is important to emphasize that some data were taken from foreign literature (mainly for the light steel framing). There is a lack of consolidated Brazilian database of CO_2 emissions for building materials. There are only some separate initiatives

in some sectors, such as cement and ceramic. When this complete environmental database for Brazilian building materials is published, the authors intend to verify the calculations and the differences in results.

For future research studies, it is recommended to evaluate other environmental aspects, such as water consumption, waste generation and recycling potential of building materials. Other Brazilian systems (both conventional and industrialized ones)

should be evaluated, such as concrete brick masonry and concrete walls, as well as other Brazilian regions.

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