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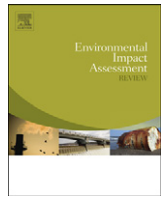
2012

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Environmental Impact Assessment Review, New York, v. 33, n. 1, supl. 4, Part 1-2, pp. 41-47, FEB, 2012

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Methodology of CO₂ emission evaluation in the life cycle of office building façades

Vanessa Montoro Taborianski, Racine T.A. Prado *

Building Systems Laboratory, Department of Civil Construction Engineering, University of Sao Paulo, Sao Paulo, Brazil

ARTICLE INFO

Article history:

Received 7 April 2011

Received in revised form 6 October 2011

Accepted 10 October 2011

Available online 15 November 2011

Keywords:

CO₂ emissions

Building façade

Life cycle assessment

ABSTRACT

The construction industry is one of the greatest sources of pollution because of the high level of energy consumption during its life cycle. In addition to using energy while constructing a building, several systems also use power while the building is operating, especially the air-conditioning system. Energy consumption for this system is related, among other issues, to external air temperature and the required internal temperature of the building. The façades are elements which present the highest level of ambient heat transfer from the outside to the inside of tall buildings. Thus, the type of façade has an influence on energy consumption during the building life cycle and, consequently, contributes to buildings' CO₂ emissions, because these emissions are directly connected to energy consumption. Therefore, the aim is to help develop a methodology for evaluating CO₂ emissions generated during the life cycle of office building façades. The results, based on the parameters used in this study, show that façades using structural glazing and uncolored glass emit the most CO₂ throughout their life cycle, followed by brick façades covered with compound aluminum panels or ACM (Aluminum Composite Material), façades using structural glazing and reflective glass and brick façades with plaster coating. On the other hand, the typology of façade that emits less CO₂ is brickwork and mortar because its thermal barrier is better than structural glazing façade and materials used to produce this façade are better than brickwork and ACM. Finally, an uncertainty analysis was conducted to verify the accuracy of the results attained.

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1. Introduction

In recent decades, there has been a major shift in office building architectural standards in major urban centers worldwide, including Brazil. Changes to façade architecture, alongside the increasing number of people and more lighting equipment per square meter, have increased the thermal load in buildings and, subsequently, their energy consumption. In the area of air conditioning systems, because of an increased demand for thermal comfort in internal environments, energy consumption from building usage has also increased, leading to a continuous increase in energy demand and environmental pollution (Shilei et al., 2005).

In order to calculate the thermal load on buildings and, therefore, their energy consumption, designers currently use computer programs to evaluate their energy efficiency. Various programs have been used for this purpose, including free programs provided by the US Department of Energy (DOE).

However, building energy consumption is not restricted to building use. When building materials arrive at the building site, they have already consumed a lot of energy during the manufacturing processes (Abeysondra UGY et al., 2007). The energy thus consumed by materials is known as “embodied energy” and is the amount of

energy incorporated into a product from the raw material extraction and manufacturing processes required to produce a finished product. It also includes the energy associated with transporting raw materials to the factory, which can considerably contribute to the overall “carbon budget” of any stage of a building construction, and the end product to the consumer.

Energy generated to obtain these materials and for other purposes, such as electricity and heat, uses the planet's natural resources and emits pollutants. Some of the most frequently used natural resources are fossil fuels. One of the main gases generated when burning fossil fuels is carbon dioxide (CO₂), the main greenhouse gas created by human activity.

Within this context, with increasing energy consumption, waning energy resources and a degraded environment, buildings have to be adapted to environmental needs. An effective tool for evaluating environmental efficiency and subsequently the energy efficiency of a specific product is the Life Cycle Assessment (LCA). This tool examines all of the material and energy inputs and outputs throughout the product life cycle, from raw material extraction to final product disposal, including the usage stage. This means that, to correctly evaluate the efficiency of a specific building, the steps in a LCA study have to be followed.

However, as products, buildings are special because they have a relatively long life, undergo changes, especially office buildings, generally have multiple functions, contain many different components, are produced locally, are normally unique, have a local impact, and

* Corresponding author at: tr. 2 no. 83, 05508-900, São Paulo, SP, Brazil. Tel.: +55 11 30915147; fax: +55 11 30915206.

E-mail address: racine.prado@poli.usp.br (R.T.A. Prado).

are integrated with infrastructure and their system boundaries are unclear. This means that a complete LCA study of a building is not a simple process, as it is for many other products (Bribian et al., 2009). Therefore, several authors have proposed simplifying the method for conducting LCA studies (Bribian et al., 2009; Kellenberger and Althaus, 2009; Malmqvist et al., 2010). Thus, the goal of this study is to use the LCA method, with certain simplifications, in order to assess the CO₂ emissions all along the life cycle of office building façades located in the city of Sao Paulo.

2. Methodology

The proposed methodology is mainly based on the LCA. However, during the usage stage, façades do not consume energy directly, but they do have an influence on the air conditioning system energy consumption. Hence, in order to assess energy consumption during this stage, a software-based thermal simulation for buildings was used. Below are the steps in this methodology and their application in simulated cases.

2.1. Defining goals and scope

In general terms, life cycle studies involve surveying energy and material flows in the raw material extraction, raw material transformation, product manufacturing, product usage, and product disposal stages.

A flow chart with life cycle inputs and outputs for façades was therefore created, as shown in Fig. 1. Notice that the actions evaluated and the life cycle inputs and outputs are presented in squares with dashed lines. Outputs will only be used to assess CO₂ emissions related to atmospheric emissions for global warming.

In this phase, the functional unit is defined. Here, the function of façade systems means to reduce environmental impacts on building functions as a whole, and to control the flow of heat between the external environment and the internal environment of the building. Therefore, the functional unit is defined as a 494 m² façade, divided into four faces (North, South, East, and West), used along the building 60-year service life, in order to obtain a comfortable internal temperature in air conditioned areas of 24 °C, in business days when the building is used.

In order to compare façades, a rectangular slab type model with 32.91 × 32.91 m was chosen. It is a typical office buildings currently found in the city of Sao Paulo, with four thermal zones mechanically ventilated and a central core with natural ventilation. In these cases, the hypothesis that the ventilation will be provided mechanically through the central air conditioning system was adopted. Below are the types of façade used in this study.

CASE A. Structural glazing façade

This type of façade uses fixed laminated glass with structural silicone on aluminum columns and beams that support the façades. Note that this type of façade must include vertical compartmentalization in accordance with fire department rules (Sao Paulo State, 2004). This is based on a separation using beams and/or parapets at least 1.2 m high, separating the openings of consecutive floors and adopting fire retardant seals using rock wool covered with a layer of refractory cement insulating plaster based on rock wool.

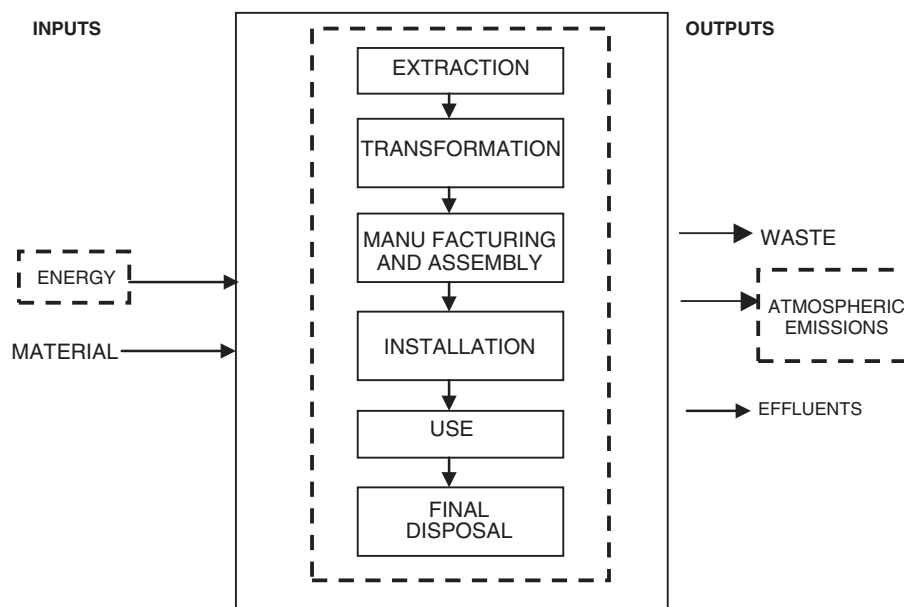
CASE B. Brick façade with mortar coating

For brick façades coated with mortar, two types of brickwork were included: concrete and ceramic blocks with nine square holes, both 14 × 19 × 39 cm wide, tall and long, laid along the longer side. Additionally, both types of brickwork would be laid and coated externally with mortar made of water, cement, hydrated lime and sand. Placement would have 10 mm of thickness and stroke 1:2:9, rough coat would have 5 mm of thickness and stroke 1:3 and level coat would have 25 mm of thickness and stroke 1:1:6.

Finally, both internal and external coatings must be painted. For the external painting, one coat of base, one coat of acrylic sealant and two coats of white façade paint were used. For internal painting, one coat of base, one coat of finishing plaster and two coats of white plaster paint were used.

Therefore, for brick façades, a window covered with a colorless floating glass was chosen, on each side of the façade, measuring 1.5 m × 24.58 m, based on a glass area of 15%.

CASE C. Brick façade with an aluminum composite panel covering



* The transport stage will be analyzed for all stage changes.

Fig. 1. Façade life cycle flowchart.

For the fixing and joint systems for these façade panels, the same metallic structural glazing was used, but the glass panel was replaced with an ACM panel. This type of façade also includes vertical compartmentalization (Sao Paulo State, 2004) and a brick structure behind the ACM panels.

Furthermore, a wall of ceramic bricks with nine holes was included, laid using mortar and internally coated with plaster, using the same specifications adopted for the brickwork system coated with mortar and painted. A window covered with a colorless floating glass was also adopted, on each side of the façade, measuring 1.5 m × 24.58 m, based on a glass area of 15%.

2.2. Façade production energy consumption survey

In this phase, the initial incorporated energy of façade system materials was calculated, based on energy resources consumed to extract raw materials, on the raw material transformation process, manufacturing and assembling the façade materials, on installing façades during building construction and on fuel consumption to transport materials between stages.

The methodology used to survey information on the raw material extraction, transformation and transport stages is presented as follows.

2.2.1. Extracting raw materials and transforming materials

In the raw material extraction and material transformation stages, the various materials used in façade systems had to be quantified in order to assess the amount of energy consumed in these stages. In order to calculate these materials, all components and accessories used in each element of each façade type were included. In this stage, the service life of the building and selected materials and/or the elements used in the façades was assessed, in order to calculate the need for any replacements while the façades are in place.

The baseline for the service life of an office building was 60 years, while the service life for components and materials was based on the information in Table 1. This table also contains the replacements required during the building service life. Useful life of EPDM was obtained from Scheuer et al. (2003), of aluminum from Freitas (2005), of painting from Tavares (2006), of silicone from Hutchinson, Pagliuca and Woolman (1995) and of other material from the manufacturing industries. In this stage, the wastage of materials used in these types of façade was estimated. Material loss indices considered were (Agopyan and Souza, 1998): sand 44%, cement 56%, gravel 38%, lime 36%, blocks and bricks 13%, mortar produced on site 18%, gypsum 30% and paints 17%.

In the raw material extraction and transformation stages, the selection of the materials involved in the process was made. Therefore, when surveying the materials, the exclusion criteria adopted was to ignore materials representing less than 1% of the total mass of materials, once the large number of materials involved in the remaining range includes the most relevant materials in terms of

environmental impact in this type of system. Therefore, the materials surveyed in respective percentage masses, in each type of façade, are included in Fig. 2.

The energy consumption for each material selected for the façades was calculated according to Fig. 2. The preference was given to primary data from the Brazilian construction industry and, when necessary, used international data, by adopting the databases from the SimaPro program (Pré consultants, 2003), switching to the Brazilian energy grid when the products were manufactured in Brazil.

2.2.2. Material transportation

In the transportation stage, the distances between the extraction points and factories for the materials used in the façades, and between these factories and the city of Sao Paulo, were calculated. Therefore, diesel consumption for truck, train and ship transport was estimated. Additionally, the following general considerations were taken into account (Teixeira and Bizzo, 2000):

- the return journeys for these methods of transportation were not included;
- the costs and emissions involved in maintaining transport vehicles were not included;
- the following values were used to calculate diesel characteristics: PC = 45,008 kJ/kg-specific weight = 852 kg/m³.
- the truck fleet was a standardized as 14-ton trucks;
- diesel consumption in rail transportation was 425 km t/L;
- consumption in sea transportation was 0.20 MJ/km t;
- diesel consumption in road transportation was calculated using Eq. (1), the model representing consumption by 14-ton trucks traveling on Brazilian highways.

$$C_{spe} = 0.2487 * 1.0096^{C_a} \quad (1)$$

where:

- C_{spe} specific diesel consumption (L/km);
- C_a truck load (t), minimum zero and maximum 14.

In order to calculate the distances traveled by each method of transport in the life cycle, the companies responsible for extracting raw materials and transforming them, with their locations, were surveyed.

2.3. Power consumption survey for façade installation and execution

Firstly, the amount of energy used to install the façades during the building construction when the façades are prefabricated outside the building site, as well as assembling them, when manufactured on site, were investigated. Therefore, for the structural glazing façade, the fact that the glass is practically slotted in, at the worksite, was taken into account.

The use of a ratchet elevator with a 1500-kg capacity, 32-m/m speed using 2 11-kW motors was included. In order to calculate the energy consumption, it was estimated that the structural glazing panels would need to be lifted 32 m. In order to create a brickwork façade coated with mortar, an electric 1.5 kW concrete mixer with a 400 L capacity, to produce mortar to build the façade and coat it on site was included. Additionally, the use of the concrete mixer for 0.306 h to produce 1 m³ of mortar was considered (TCPO, 2009).

In terms of vertical transport for the mortar produced on site, the brickwork, frames and glass for the windows, the calculations included the elevator previously referred to. In terms of brickwork façades coated with ACM, because of the construction system used, the work involved includes both assembling and installing the panels, similarly to the situation described for the structural glazing façade

Table 1
Project service life and replacement material used on façades.

Component	Material	Useful life (years)	Replacement
Accessories	EPDM	35	1
Frames	Aluminum	60	0
Fire protection	Rock wool	60	0
Glass sheet	Glass	60	0
ACM Panel	Aluminum and PEBD	60	0
Metal frames	Aluminum	60	0
Painting	Plaster paint	12	5
	Façade paint	8	7
Internal lining	Gypsum	60	0
External coating	Mortar	60	0
Silicone	Silicone	30	2

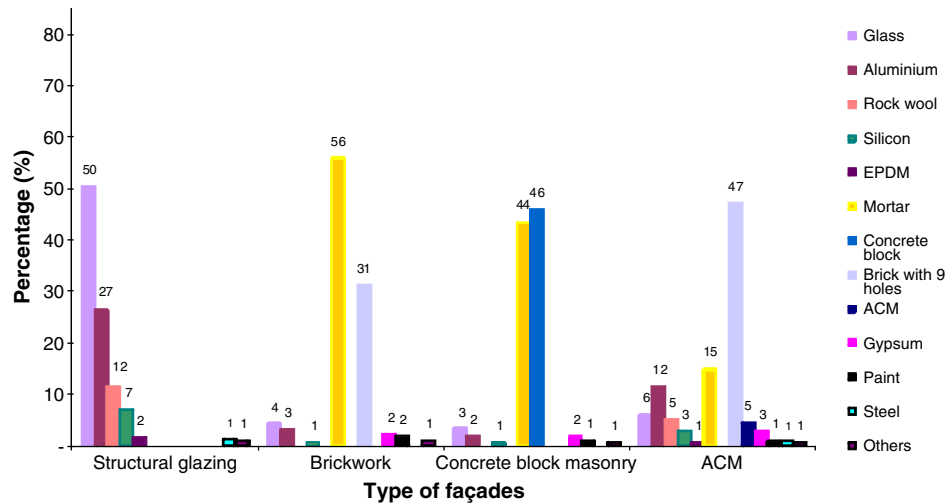


Fig. 2. Comparative volume of materials used to produce façades.

and the brickwork façade coated with mortar. Therefore, the same equipment as the structural glazing and brickwork façades was employed.

2.4. Computer simulation to evaluate energy consumption in air-conditioning systems

In this stage, the *Energy Plus* simulation program was used to calculate the air-conditioning system power consumption, in each type of façade system, based on the same occupation, geometry and weather conditions. Therefore, an air conditioning system was adopted, the performance of which was measured using criteria adopted in Brazilian building designs. The characteristics of the compact air-conditioning system were based on 0.85 for total ventilator efficiency, 0.92 for ventilator motor efficiency, 0.25 for ventilator pressure variation and 3.5 for COP.

For structural glazing façades, the simulations were conducted using uncolored and reflective 6 mm glass, while for brickwork façades coated with mortar, calculations were based on ceramic bricks and concrete blocks, and for the brickwork façade covered with ACM, ceramic brick and ACM panels were used. The internal loads from people, illumination, and electrical devices were taken into account, because the objective was only to evaluate the façade impact on air conditioning electricity consumption.

In order to calculate the thermal performance of a façade, the calculations were based on the thermal properties of its component materials, presented in Table 2. Thermal properties of concrete, gypsum and ceramic brick with 9 holes were obtained from ABNT NBR 15220 (2005), of nylon carpet from Figueiredo (2007), of ceiling air space resistance from Dataset Energy Plus and ACM panel from the manufacturing industry.

For the structural glazing façades, colorless glass with normal solar transmittance of 0.74 and reflective glass with normal transmittance

of 0.04 was adopted. The non-opening window type was adopted, which means that the internal air can only be renewed by the air-conditioning system. However, the external air infiltration volume of 0.2 m³ per second was adopted, caused by open doors and/or gaps in windows and glass panels. External airflow was based on 0.4 L per second * square meters, for intermediate level external airflow for ventilation in mid-level density offices (ABNT NBR, 16401, 2008).

The operating time adopted for calculations was from 8 AM to 6 PM, Monday to Friday. Furthermore, the model thermal behavior during a typical year based on air conditioning system usage was only for business days, i.e., 22 days a month.

2.5. Energy consumption survey for façade disposal

When a façade comes to the end of its service life, its materials must be disposed off appropriately. Disposal alternatives include recycling and reuse. When possible, the materials can be reused, or disposed at a landfill if they cannot be recycled. All of these alternatives consume energy either to transform the recycled material or to transport it to the reuse location or landfill.

The approach adopted was that residual material components from façades would be sent to landfills, selective collection locations or temporary storage locations, and that transporting these materials to their destination would involve a 50-km trip, using 14-ton trucks, based on the same diesel consumption used in the material transportation stage.

2.6. Surveying CO₂ emissions during façade life cycles

In this stage, the amount of CO₂ contributing to global warming that would be emitted by power companies in each stage of the life cycle was estimated, and the fuel burned during transportation and

Table 2
Thermal properties of opaque materials.

Material	R (m ² K/W)	d (kg/m ³)	λ (W/m K)	c (kJ/kg K)	α _{solar}	α _{thermic}	α _{visible}	References
Concrete	–	2300	1.75	1.00	0.725	0.90	0.725	ABNT NBR 15220
Gypsum	–	875	0.35	0.84	0.20	0.90	0.20	ABNT NBR 15220
Nylon carpet	0.367	–	–	–	0.75	0.90	0.75	Figueiredo (2007)
ACM panel	0.0103	–	–	–	0.05	0.05	0.05	ABNT NBR 15220; Alcan Composites ¹
Concrete block wall	0.3215	–	–	–	0.725	0.90	0.725	–
Ceramic brick with 9 holes	0.5084	–	–	–	0.725	0.90	0.725	ABNT NBR 15220
F05 Ceiling air space resistance	0.18	–	–	–	0.92	0.90	0.92	Dataset Energy Plus

¹ Data obtained from the product catalogs of Alcan Composites.

Table 3
CO₂ emission factors in material transformation and transportation process stages.

Material	CO ₂ emission factor ((kgCO ₂ /t of material)	
	Transformation process	Transport
ACM	10324	147
Aluminum ¹	3162	70
Soda	383	116
Lime	1270	196
CP II – E	676	216
CP V – ARI	722	216
EPDM	195	729
Gypsum	433	1612
Rock wool	685	57
Silicon	623	310
Ceramic brick	169	130
Paint	0.3	1759
Glass	440	390

¹ Based on production of alumina and aluminum.

by the industrial processes need for some of the inputs used, based on the energy resources consumed when producing façade materials.

In this phase, there is more than one process used to generate the energy used during the façade life cycle. This energy can be thermal, produced by burning fossil fuels, or electrical, from thermoelectric and hydroelectric power plants or alternative power sources.

On its institutional webpage, the Brazilian Ministry of Science and Technology (MCT) has published the average monthly and annual CO₂ emission factor for generating 1 MWh of electrical energy in the national system, from 2006 onwards (MCT, 2010). Therefore, the 2006, 2007, 2009 and 2010 averages were used, which resulted in a value of 0.0277 tCO₂/MWh. The 2008 data were excluded because this was an atypical year for the Brazilian energy grid in function of weather conditions.

Regarding energy from fossil fuels, the carbon emission factors differed from 15.3 tC/TJ, for natural gas, to 29.9 tC/TJ, for wood and charcoal. Values were obtained in MCT (2009), for national fuel, and DOE (2007), for fuel in other countries.

However, not all of the carbon contained in the fuel will be oxidized because, in practice, combustion is never complete, leaving a small amount of unoxidized carbon in the ashes and other by

products. Therefore, the fraction of oxidized carbon when burning each type of fuel was also included. Fractions of oxidized carbon were also considered and were between 0.858 and 0.990. Values were also obtained from MCT (2009) and DOE (2007).

In addition to the thermal and electrical energy emissions from façade production, some industrial processes emit gases which are created from the chemical mixtures used to produce the materials. Table 3 presents the factors adopted for CO₂ emissions in the transformation stage, industrial process emissions (Frischknecht et al., 2007), energy used to produce façade materials, and in the transportation stage, based on the emission factor published by the MCT (2006), 2.799 g CO₂/L, for heavy diesel-fueled vehicles (MCT, 2009).

2.7. Uncertainty analysis

During a life cycle inventory, inputs and outputs are based on average values. This description includes some uncertainty because the average values are not very accurate and there may be a discrepancy between the values surveyed, measured or informed and actual values (Weidema and Wesnaes, 1996).

Therefore, a sensitivity analysis and an uncertainty analysis based on the Pedigree matrix by Weidema and Wesnaes (1996) were conducted to evaluate the quality of the results obtained during this study.

3. Results

The results obtained for CO₂ emissions during the life cycle of the types of façade studied and the contribution from each stage towards the final result of emissions are presented in Fig. 3. According to this figure, the façades which emit most CO₂ are the structural glazing façades using colorless glass, followed by ceramic brick façades covered with ACM, structural glazing using reflective glass, and façades built using brick and covered with mortar.

On the other hand, the structural glazing façade has a major impact because of the high level of energy consumption while in use; however, the new technologies for reflective glass may be able to minimize this impact and improve the environmental performance of this type of façade, as demonstrated herein.

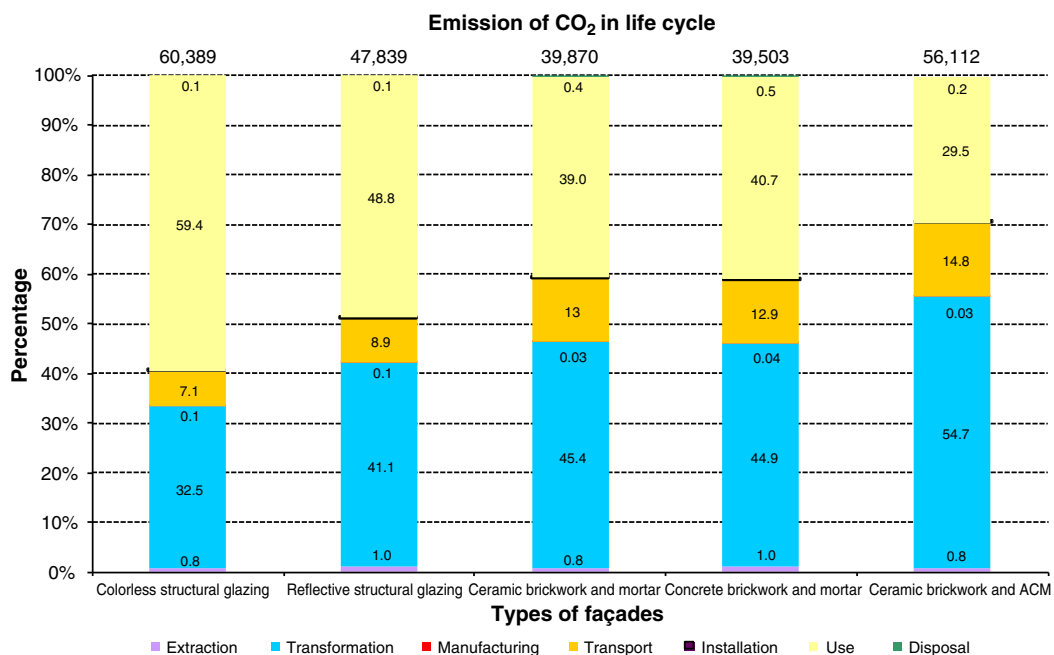


Fig. 3. Contribution of each life cycle stage to CO₂ emissions in %. Obs.: Because of the low level of emissions, the installation stage does not appear in this figure.

Table 4
CO₂ emission by façade area.

Type of façade	Emission of CO ₂ (kg CO ₂ /m ² of façade)
Structural glazing with colorless glass	122
Structural glazing with reflective glass	97
Concrete block masonry coated with mortar	80
Ceramic brick masonry coated with mortar	81
Ceramic brick masonry coated with ACM	114

In order to compare CO₂ emissions by type of façade and in future studies, the emissions by façade area were divided. Table 4 presents the results.

Finally, Table 5 presents the final results of the weighted level of uncertainty for CO₂ emission results throughout the life cycles of the façades surveyed. The final result is the average of the partial results of the uncertainty levels for each stage analyzed, multiplied by the contribution of each stage in the life cycle of each type of façade.

4. Conclusion

Based on the results obtained by developing and applying the CO₂ emission assessment during office building façade life cycles, the façades which emit most CO₂ are the structural glazing façades using colorless glass, followed by ceramic brick façades covered with ACM, structural glazing using reflective glass and façades built using brick and covered with mortar. These results confirm that conventional building of masonry and mortar is still the most suitable for the Brazilian climate similar to that of São Paulo city.

In terms of emissions, the more important life cycle stages which need to be analyzed are the usage, material transformation and transport stages, because of their impact on the final result. During façades usage, energy consumption is quite high, mainly that of electricity, and the type of façade has an impact on air conditioning energy consumption. This means that the electricity demand during this stage has a major impact on the power generation system, resulting in the need for more generating infrastructure.

On the other hand, the energy produced in Brazil comes predominantly from hydroelectric power plants which produce very little CO₂ as compared with thermal power plants. Therefore, the power produced in Brazil emits less CO₂ than in many other countries where power is produced by thermal power plants. However, this is the current state of the country and it could change if the Brazilian grid starts producing more power from fossil fuels. Therefore, to reduce the impact of power consumption in the stage of the façade life cycle is a crucial issue.

In terms of CO₂ emissions, during the usage stage, structural glazing façades with colorless glass emit most CO₂, with this stage contributing with 95% of emissions, followed by structural glazing using reflective glass (49%), brickwork façades covered with ACM (approximately 30%), and finally brickwork façades covered with mortar (40%).

The results were obtained based on the façade impact on the thermal load calculation, without considering internal loads which also affect buildings, such as people, illumination and electronic

Table 5
Level of weighted uncertainty for façade types.

Type of façade	Average uncertainty factor (%)
Structural glazing with colorless glass	12
Structural glazing with reflective glass	13
Concrete block masonry coated with mortar	10
Ceramic brick masonry coated with mortar	10
Ceramic brick masonry coated with ACM	12

equipment. If the internal loads are taken in the results, the increased energy consumption will have a much greater impact on CO₂ emissions during this stage.

Looking at the material transformation process, industrial processes in Brazil consume a lot of energy, approximately 36% of all the energy consumed in the country while in many other countries, the industry consumes no more than 26% (Henriques et al., 2010).

According to the survey results, materials causing the highest levels of CO₂ emissions in the transformation process are ACM, aluminum, lime and cement. ACM emissions are based on the fact that the material is imported, mainly from the USA and China, which means that the energy emissions from these countries should be taken into account, as energy production is based on mineral coal which emits a lot of CO₂. Therefore, ACM emissions were calculated at 10,472 kg CO₂/t, based on US ACM production. On the other hand, simulating ACM production in Brazil, emissions would drop to 6566 kg CO₂/t, because the Brazilian power generation system produces less emission.

Therefore, depending on the material used, the stage emitting the most CO₂ for brickwork façades covered with mortar and ACM is the material transformation process. Therefore, the fundamental step when studying construction product life cycles is evaluating CO₂ emissions from construction materials.

It is therefore essential for the industry to provide environmental statements for these products, informing energy consumption and emissions during their life cycles. Finally, in the material transport stage, the predominance of road transportation in Brazil significantly increases CO₂ emissions for building materials. This is shown by certain products such as paint, plaster and EPDM, for which trucks travel long distances to deliver the product to the construction site; this has a much greater impact on emissions than the transformation process and produces a much higher level of emissions than the longer distances traveled by ship, as is the case for silicone and ACM.

Therefore, selecting materials from suppliers located near the site can reduce CO₂ emissions and minimize the distances traveled when transporting these materials. Furthermore, the Brazilian construction industry presents a high level of material wastage and uses materials with high levels of CO₂ emissions, such as cement, lime and aluminum, caused by the chemical reactions from their production processes.

Acknowledgment

Authors would like to thank the financial support granted to this work by Fapesp, the State of Sao Paulo Research Foundation.

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Vanessa M Taborianski Bessa Ph.D. in Civil Engineering from the Polytechnic University of São Paulo (2010). She has experience in Civil Engineering with an emphasis on sustainable construction, mainly in the following themes: water heating, energy, global warming, life cycle analysis and air conditioning.



Racine T. A. Prado Ph.D. in Civil Engineering from the University of São Paulo (1996). He is currently an associate professor at Polytechnic University of São Paulo. He has experience in Building Systems, acting on the following themes: conservation and rational use of water and energy, water heating, thermal comfort, air conditioning, building automation and environmental sustainability of buildings