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Variability in the life cycle of concrete block CO_2 emissions and cumulative energy demand in the Brazilian Market

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HIGHLIGHTS

- Demonstrates the variability within manufacturers of the same construction products.
- Shows that LCA results of a specific technological route should be used with caution.
- Unveils a cleaner production potential within the concrete blocks manufacturing sector.
- Analysis based on original life cycle data of the Brazilian material construction sector.

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ABSTRACT

In this study we estimate CO_2 life cycle emissions and cumulative energy demand (CED) of several concrete block manufacturers in Brazil. The assessment is based on original data collected from 29 concrete block producers in distinct Brazilian regions. Blocks with different strengths were assessed. We have combined original data with information from the literature, and most of the assessment was based on information representing the domestic context. Considering the same technological route and the various block types, CO_2 emissions vary 2.6–3.3 times, whereas CED varies 3.5–4.0 times. Cement consumption was responsible for most of the differences, and the effect of low clinker content cement was not decisive. Although Brazil has a vast territory, the impact of transportation was small. Results demonstrate that there is a potential for cleaner production strategies within the sector. Simplified life cycle assessment tools, such as the one applied in this study, are relevant to pursue effective solutions for reducing energy consumption and achieving low carbon solutions within the construction components industry.

1. Introduction

Construction is responsible for the extraction of a significant amount of natural resources, especially targeting cementitious materials. The mass of cement produced in 2013 was 3.7 billion metric tons [1]. This amounts to an apparent consumption of 22 billion tons of aggregates and 2.5 billion cubic meters of water [2]. Besides that, around 5.3% of the global CO_2 emission comes from cement manufacturing [3], and its share is rapidly growing.

Concrete blocks are important global cementitious products. Nevertheless, there are few studies assessing their life cycle environmental impacts. Comparative assessments between concrete and ceramic blocks applied in the construction of 1 square meter of walls are more usual [4–6], including database values (INIES[1]; ITeC/BEDEC[2]). Table 1 presents typical CO_2 emission and energy consumption values for concrete blocks from the literature.

Although most life cycle assessments (LCA) intend to generalize their findings, usually only a single emission factor is used to represent the inventory flows of concrete blocks of a given country or region. Few studies rely on original data. For instance, the Athena Institute [7] has considered a single formula to represent concrete blocks of different cities in Canada. The study does not show any evidence supporting either the formula representativeness or its expected variability. The Portland Cement Association (PCA) has

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[1] http://www.base-inies.fr/Inies/default.aspx: French database accessed in January 2015 – item: "Mur en maconnerie de blocs en beton".
[2] http://itec.cat/nouBedec.e/bedec.aspx: Spanish database accessed in January 2015 – Item: E61BCC11 "pared para cerramiento".

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Table 1
Typical CO_2 emissions and energy consumption values for concrete blocks fabrication. CTG – cradle to gate; CTGr – cradle to grave.

Dimensions (cm)	Energy (MJ/block)	CO_2 emission ($kgCO_2$/block)	Source	Boundary	Observations
14 × 19 × 29	13.0	2.2*	[5]	CTG	Brazil 16,67 blocks/m^2
14 × 19 × 39	25.72	2.76*	[4]	CTGr	Brazil Estimated
20 × 20 × 40	21.31	2.10	[7] [9]	CTG	Vancouver, Canada
	22.73	2.22			Calgary, Canada
	24.39	2.34			Winnipeg, Canada
	22.25	2.15			Toronto, Canada
	23.67	2.25			Montreal, Canada
	23.80	2.26			Halifax, Canada
20 × 20 × 40	12.30	1.61	[9]	CTG	USA

Note: *Data in $kgCO_2$ equivalent.

evaluated a single concrete block formula to assess the impacts of a standard block traded in the large North American market [9]. However, technical specifications of the product such as strength are not presented. Therefore, information regarding material and energy flows related to the life cycle of concrete blocks is scarce.

The assumption that companies applying the same technological route present similar impacts from their production processes is customary in LCA studies. Nevertheless, a meta-analysis of the flows of plastic concrete in Brazil and other 28 countries has demonstrated the existence of a considerable variability on the energy and mass flow of concretes with the same mechanical strength, the same cement type, and similar technological route [10]. Such variability is particularly related to variable cement consumption, which is responsible for more than 90% of the CO_2 emissions. Concrete with 30 MPa strength might be produced with a share of concrete between 250 and 450 kg/m^3. In addition, considering Brazilian conditions, national standards allow for a wide range of clinker content for each cement type, and its exact amount is not disclosed. This adds more uncertainty regarding CO_2 emissions because different types of cement might present the same amount of clinker; and therefore, the same emission factor [11].

Considering differences in the performance of concrete block making machines, mixers, formula strategies, use of thermal cure, aggregates variability (for instance, specific gravity and shape), and cement variability allied to differences in their emission factors, significant differences among concrete block producers are expected. Therefore, the objective of this study is quantifying CO_2 emissions and the cumulative energy demand (CED) in the fabrication of concrete blocks among 29 of the best Brazilian companies, with similar technological route, reporting also the uncertainty and the variability in the sample. The result might be stored in a national life cycle inventory database and will be used as a tool to promote cleaner production among concrete block manufacturers.

2. Methodology

All concrete block manufacturers certified by the Brazilian Concrete Block Association (BlocoBrasil) were invited to participate in the study. Out of 45 companies, 29 companies have accepted. Besides the engagement with socially responsible practices, participating companies assumed part of the project costs. The initiative entails a pilot project to apply a streamlined LCA framework to the construction material sector as part of the Brazilian LCA Program (PBACV). Therefore this is not a representative sample of the Brazilian concrete block production. It is however, up to this moment, the most comprehensive study relying on original data.

First, in order to collect detailed data on each company's production process, a survey form was prepared. After testing the form with 3 companies, the form was simplified to reduce the level of details, and facilitate data collection. The survey forms were implemented on spreadsheets and companies were responsible for their own data collection. Training on LCA methodology and details on how to fill out the form was provided to the technical staff of the companies.

The form required mass, quantity, consumption and type of cement over a 12 month period for each strength class (4, 6, 8, 10, and 12 MPa) of concrete blocks with dimension of 14x19x39 cm. Data is regarded from 2012 to 2013. Additionally, information related to the main material (cement and aggregates) and energy inputs consumed over the same period was also requested. Consumption of additives and color dyes were not evaluated because their mass is negligible compared to the total mass of products, below 1%. The total throughput of the plant was used to carry out mass based allocation procedures. This was the case for electricity and fuel consumptions that were assessed at the whole plant level. The amount of energy per block was determined based on the mass of a single block divided by the total mass of products over a given period.

After preliminary data analysis, companies with the extreme and average results were audited by a team of the *Serviço Nacional de Aprendizagem Industrial* (SENAI). Final results were calculated after the companies revised the data. Nevertheless, a few outliers (4 companies with divergent results) were perceived as inventory errors and were not considered in the final results.

2.1. Streamlined LCA of concrete blocks

The study adopted a cradle to gate system boundary. Therefore, in order to determine the CO_2 emission and the cumulative energy demand of the analyzed concrete blocks, we considered the raw materials allocated to each product, the fuel consumed for the transport of the material inputs, and the electricity and fuels consumed within the plant. The functional unit was defined as a unitary concrete block.

In order to determine the final indicators, energy and CO_2 emission factors of the main inputs were collected from the literature and, whenever it was possible, national information was prioritized. Because such data are sensitive to production processes, availability of local resources, production efficiency, and the amount of material used [12], we considered a range of values for raw material inputs instead of single average values.

Because a range of clinker share is allowed in the composition of domestic cement mixes, local resource availability affects both the CED and CO_2 emissions of cement manufacturing. Based on information from three large Brazilian companies that participate in the Cement Sustainability Initiative (CSI) of the World Business Council for Sustainable Development (WBCSD), we have determined the range for energy and CO_2 emission factors of different cement types that were used by the assessed companies (Table 2). Supplementary cementitious materials are usually added at the

Table 2
CED and CO_2 emissions per cement type. Source: CED – WBCSD[a]; Emission factor [13].

Type of cement	Supplementary materials	CO_2 emission factor ($kgCO_2/t$)			CED (MJ/t)		
		Minimum	Maximum	Max/Min	Minimum	Maximum	Max/Min
CP II-F	Filler: 6–10%	735	770	1.1	3096	3240	1.1
CP II-Z	Filler: 0–10% Fly ash: 6–14%	616	770	1.3	2592	3240	1.3
CP V	Filler: 0–5%	778	821	1.1	3276	3456	1.1

[a] Calculated through heat consumption over five years (2008–2012 – www.wbcsdcement.org/GNR-2012/Brazil/GNR-Indicator_329-Brazil.html) and the quantities of clinker allowed for Brazilian standards.

Table 3
CO_2 emission and CED of the aggregates informed by participating companies.

Raw materials	CO_2 emission factor ($kgCO_2/t$)			CED (MJ/t)			Sources
	Minimum	Maximum	Max/Min	Minimum	Maximum	Max/Min	
Natural sand	4.2	9.6	2.3	55	109	2.0	[14,15]
Industrial sand	1.3	1.9	1.4	17	42	2.5	[16]
Gravel	1.2	1.9	1.6	14	55	3.9	[16,17]
Fly ash	0.0	0.0	–	0	0	–	Waste from other industry
Recycled aggregate	0.8	1.8	2.3	14	21	1.5	[18]

cement plant and only one company did add fly ash directly to concrete mixer. Because fly ash is a secondary material it was considered CO_2 neutral.

Information regarding the impacts of aggregates production in Brazil is scarce and inaccurate. Information regarding the impact of aggregates was not requested, a range of values based on the literature was adopted. Fuel and electricity consumption based on these secondary sources was used to determine CED and CO_2 emissions due to quarry and processing of aggregates. The range of values is presented in Table 3. These values were computed based on energy consumption and emission factors collected from the literature, which are presented in Table 4. If available, the life cycle of products was considered in addition to fuels heat content and direct emissions. This was the case for diesel, gasoline, ethanol, natural gas, firewood, LPG and fuel oil.

2.2. Calculation methods

CED related to each concrete block was calculated based on the embodied energy of each material and energy input, considering transport and direct energy needs within the plant. The result is presented in MJ/block. Eq. (1), in which CED_{rm} are values taken from Tables 2 and 3 and $m_{rm.bl}$ is the mass of cement plus aggregates contained in the product, was used to estimate the CED.

$$CED_{rm.bl} = \sum(CED_{rm} \times m_{rm.bl}) \quad (1)$$

Although cement consumption per block was provided by companies; the amount of aggregates requested in the survey form was related to the total production of the plant over the period. Therefore, apparent aggregates consumption was estimated based on the mass of a unitary block (m_{bl}), which was informed by the company. We have assumed that blocks are made of cement ($m_{cim.bl}$), aggregates ($m_{ag.bl}$), and water (m_w). The mass of water is related to the water that reacts with cement (20% of the cement mass) plus the water that is in equilibrium with the atmospheric moisture (5% was adopted), as shown on Eq. (2). The mass of aggregates required for each block was calculated based on Eq. (3).

$$m_w = 20\%(m_{cim.bl}) + 5\%(m_{bl}) \quad (2)$$

$$m_{ag.bl} = m_{bl} - m_{cim.bl} - m_w \quad (3)$$

Because the share of each type of aggregate was not requested ($m_{ag.n}$), each one was calculated based on the total consumption of the factory ($m_{ag.fact}$) according to Eqs. (4) and (5).

$$m_{ag.fact} = \sum_n m_{ag.n} \quad (4)$$

$$\%_{ag.n} = \frac{m_{ag.n}}{m_{ag.fact}} \quad (5)$$

Aggregates consumption was essential to determine the impact share due to each material input and its transport. Therefore, aggregate consumption for each block was estimated based on the total aggregate mass in each product and the share of each type (Eq. (6)).

$$m_{ag.n.bl} = \%_{ag.n} \times m_{ag.bl} \quad (6)$$

In order to estimate the CED due to the transport of raw material inputs ($CED_{transp.bl}$), it was necessary to estimate fuel consumption first. Fuel consumption was based on the trip to deliver the material, and the return of the empty truck was ignored. The consumption of diesel oil was estimated based on the distance and the material mass that was provided by the companies. First, the number of trips (NT) required to transport the total material mass (m_{rm}) was determined based on the capacity of the vehicles (m_{transp}).

$$NT = \frac{m_{rm}}{m_{transp}} \quad (7)$$

The volume of diesel oil per mass of material hauled by truck (DC_{rm}) was estimated based on Eq. (8), in which CF is the consumption factor per transported mass multiplied by distance, TMT is the total mass transported (vehicle plus material mass) and DIST is the distance traveled. Values of CF were collected from a previous Brazilian study, in which the range between 0.006 and 0.022 L/t km [24] was representative for the trucks used by the companies to haul construction materials.

$$DC_{rm} = \frac{CF \times NT \times TMT \times DIST}{m_{rm}} \quad (8)$$

Diesel consumption per mass unit of materials transported by train was estimated using the emission factor (EFT) range based on the *1° Inventário Nacional de Emissões Atmosféricas do Transporte Ferroviário de Cargas* [25]. The EFT range in the document is

Table 4
CO_2 emission factors and CED of energy inputs per functional unit (FU).

Energy input	FU	CED (MJ/FU)	EF ($kgCO_2$/FU)	Source: CED	Source: EF
Diesel oil	l	37.3	3.3	[19]	[19]
Gasoline	l	34.8	2.7	[19]	[19]
Hydrated alcohol	l	21.5	0.4	[19]	[20]
Natural gas	m^3	41.3	5.4	[20]	[20,21]; GHG Protocol spreadsheet[a]
Firewood (wood planted)	t	6,204.3	689.9	[22]	[22]
		13,734.3	1,512.2		
Firewood (waste-planted/ native)	t	6,073.0	0.0	[22]	Waste from planted or native forest
		12,980.0	0.0		
Electricity	kWh	6.01	0.06	Calculated based in BEN 2013[b]	MCT – average of 2011, 2012 and 2013[c]
LPG	t	56,140.0	3,759.6	[19]	[19]
Black liquor	t	11,970.0	0.0	[23]	Waste from cellulose industry
Fuel oil	m^3	49,786.0	3,835.0	[20]	[20]
Shale oil	t	38,100.0	2.792.7	[21]	GHG Protocol spread sheet[a]

[a] Spreadsheet by *Programa Brasileiro* GHG Protocol: http://ghgprotocolbrasil.com.br.
[b] It was considered the mainly sources of Brazilian electricity matrix: hydro, biomass, natural gas, oil products, nuclear, and coal and coal products [23].
[c] http://www.mct.gov.br/index.php/content/view/321144.html#ancora.

between 0.0049 and 0.0364 $kgCO_2$/t km. Accordingly, total CO_2 emissions per mass of transported material ($mCO_{2.rm}$), was calculated based on Eq. (9).

$$mCO_{2.rm} = \frac{EFT \times NT \times m_{transp} \times DIST}{m_{rm}} \quad (9)$$

Next, the diesel volume per mass of transported material (DC_{rm}) was determined based on Eq. (10), in which EF_{diesel} is the CO_2 emission factor per liter of diesel (Table 4).

$$DC_{rm} = \frac{mCO_{2.rm}}{EF_{diesel}} \quad (10)$$

The calculation of the final indicators considered the best and the worst case scenarios, that is, the shortest distance with the largest mass transported per trip and the longest distance with smallest mass transported per trip, respectively. Accordingly, CED due to railroad freight was calculated based on Eqs. (11) and (12), in which EE_{diesel} is energy embodied of diesel fuel. DC_{bl} is the total diesel volume required to transport the materials needed to fabricate one block ($m_{rm.bl}$).

$$DC_{bl} = \sum DC_{rm} \times m_{rm.bl} \quad (11)$$

$$CED_{transp.bl} = EE_{diesel} \times DC_{bl} \quad (12)$$

Finally, energy consumed within the factory ($CED_{fact.bl}$) was allocated based on the mass of the products. The share of each block in the total production of the plant was determined by the ratio between the total mass of each product and the total mass produced by the plant over the considered period. Eq. (13) was used to estimate and allocate the consumption of each energy carrier within the factory ($CE_{fact.n}$) to each product (CE_{prod}). Thus, energy consumption for each block (CE_{bl}) was estimated based on Eq. (14), in which the amount of each block produced is QTD_{prod}. Eq. (15) was used to estimate the CED per piece, and CED_{EI} is the cumulative energy demand for each energy input that was consumed at the factoring ($CED_{EI.n}$), and is presented on Table 4.

$$CE_{prod} = \%bl \times CE_{fact.n} \quad (13)$$

$$CE_{bl} = \frac{CE_{prod}}{QTD_{prod}} \quad (14)$$

$$CED_{fact.bl} = \sum CED_{IE.n} \times CE_{bl} \quad (15)$$

CO_2 emission and CED were estimated likewise for each block, based on the same assumptions. CO_2 emissions account for material production, transport fuel, and direct energy consumption at the plant. Results are presented in mass of CO_2 per block. Eq. (16) was used to assess CO_2 emission related to materials acquisition, and EF_{rm} is the CO_2 emission factor presented on Table 2 and Table 3.

$$CO_{2\,rm.bl} = \sum (EF_{rm} \times m_{rm.bl}) \quad (16)$$

CO_2 emission from freight was determined based on diesel oil consumption that was estimated by Eq. (17). EF_{diesel} is the CO_2 emission factor presented on Table 4.

$$CO_{2\,transp.bl} = EF_{diesel} \times DC_{bl} \quad (17)$$

Finally, CO_2 emission related to the fabrication process within the plant was calculated based on Eq. (18). All energy carriers consumed were considered and their respective CO_2 emission factors ($FE_{IE.n}$) are presented on Table 4.

$$CO_{2\,fact.bl} = \sum FE_{IE.n} \times CE_{bl} \quad (18)$$

3. Results and discussions

The unitary mass of blocks directly affects the amount of energy and materials embodied in the product. Since the block has standard dimensions, in principle it is expected to have low variation between producers. Nevertheless, a significant variability of mass was found in the market. First, the higher mass has the higher strength class (Mass = 0.108 SC + 12.03, where Mass is in kg, SC strength class in MPa, R^2 = 0.2616). This is expected because different strength implies different porosity. However, there is a high dispersion within each strength class, typically around 2 kg or 16% for each class. The Brazilian standard NBR 6136 [26] sets the dimensions and the width of the block walls, and some variance is accepted. Such variance, in addition to differences in aggregates density and block porosity, yields a considerable discrepancy in the final product mass and impact energy and emission flows. Scaling errors and moisture content estimation might affect results as well. It also might be possible that part of observed mass variations result from different strategies to obtain the minimum mechanical strength, intertwined with porosity (vibration or mix composition) and concrete block walls width.

Cement is the major driver for cumulative energy demand of concrete blocks. Reducing cement mass or selecting a cement type with low CED would reduce products' CED. Furthermore, in some Brazilian regions energy is applied to accomplish thermal curing. A solution to reduce CED in such cases might be improving the

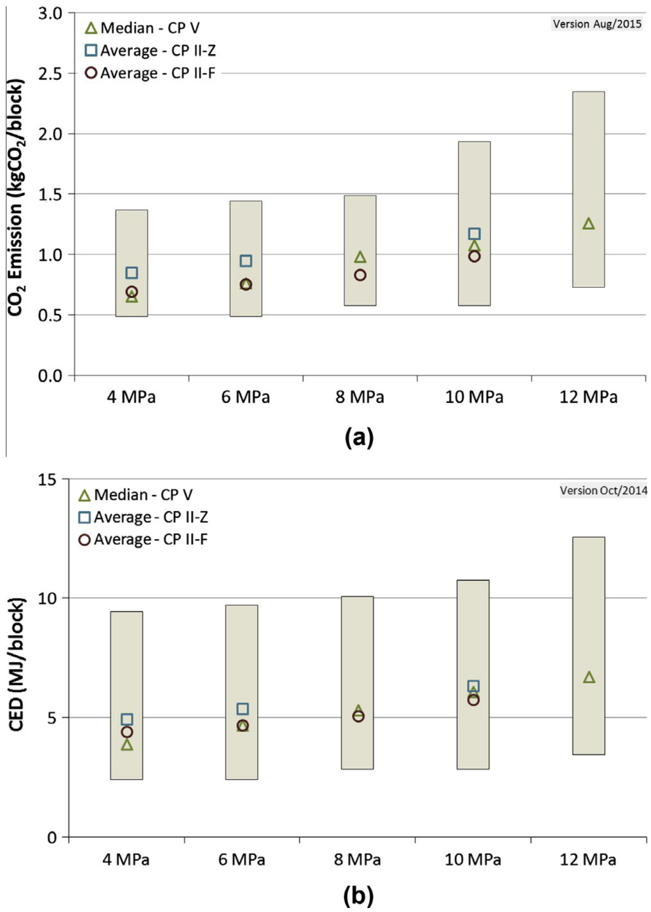

Fig. 1. Result ranges of standard blocks, with median/average per type of cement. (a) CO_2 emission; (b) cumulative energy demand.

thermal insulation of the curing chamber; and therefore, reducing heat losses of the process.

Fig. 1 presents CO_2 emissions and CED ranges for concrete blocks with different strengths, with the median per type of cement. Ranges between maximum and minimum CO_2 emissions and CED are due to the variability of inventory values among companies and emission factors' uncertainty. Differences between companies are due to factors such as: mix composition, materials' transportation modes and distances, and variation in block mass. Variability is significant and the difference between the maximum and the minimum values is 2.6–3.3 times for CO_2 emissions, and 3.5–4.0 times for CED. About 26 of the assessed companies have used CP V cement; one used CP II-Z; one CP II-F; and another one CP IV type. However, results based on the former company are not plotted on the graph because it probably denotes as inventory error. Each participating company knows the estimated CO_2 and CED values from its own products. Therefore, ranges work as a benchmark, allowing company managers to compare their performance within the entire group. This strategy aims to encourage laggards to seek improvement and promotes cleaner production within the concrete blocks manufacturing sector.

All minimum CO_2 emission values are related to the same cement type (CP V), which contains the greater clinker share. This cement type is also responsible for all maximum results. Therefore, according to our assessment, CO_2 emissions were not driven by clinker share. Although clinker content affects cement manufacturing CO_2 emissions, and is incorporated in the mainstream sector's strategy to mitigate emissions [27,28], it does not necessarily reduce cement containing products emissions as suggested in the literature [29,30] and certification schemes such as LEED [31,32]. Consequently, other factors that affect the amount of cement might be considered to mitigate emissions, even if low clinker content cements are not available.

Indeed cement consumption was the main CO_2 emissions driver, and a wide range of cement proportions was observed for the production of the same standard block. The maximum cement consumption is 2.7 times greater than the minimum value. Characteristics of the pressing machine used to mold the blocks is probably an important cement consumption driver that affects CO_2 emissions and CED, because greater efficiency compaction means less cement is needed to achieve the minimum standard strength.

All maximum CO_2 emission results are related to the greatest cement consumption in each strength class. However, the greatest CED values and the smallest results are not necessarily related to the greatest and the lowest cement consumption, respectively. Minimum CED and CO_2 emission values are observed in the same company but that is not the case for the maximum values. Clearly the minimization of CED and CO_2 are not driven only by cement content but depend on other factors as well.

Provided a given design, particle characteristics, aggregate's distribution and shape, cementitious materials, water, and additives content, directly affect the rate of compaction obtained with a given amount of energy – a machine's attribute. Therefore, these factors affect the quantity of cement required to reach the specified standard, and the subsequent CO_2 emissions and CED. Some companies might implement strategies to set concrete mixes, including the selection of aggregates, so that cement consumption is minimized and by extension concrete's carbon footprint. Some companies rely on cement suppliers 30–584 km away, and probably due to technical reasons would rather use CP V hauled over long distances than other types, with lower clinker content but negative impacts on the mix. Sometimes it is possible that the aggregate quality and the available cement in the region are limiting factors that are beyond the manufacturer's control.

It is hard to compare results from this assessment with results from other published studies. The [4] has considered other greenhouse gases (GHG) besides CO_2. However, if we consider that CO_2 is the main GHG emitted and that in our assessment only CO_2 was inventoried, the Quantis values would be among the maximum values of our ranges. In comparison, some of the Brazilian producers release only one third of the maximum emissions. Similarly to the majority of LCA results, the Quantis study represents the wide variability of a country's industry and concrete block strengths by means of a single value. Results from [7] and from [9] assessments also present values similar to our higher results. The first study is the only one that addresses the variability between different Canadian regions. However, the variability is based on energy efficiency differences in the cement production processes of distinct regions, and the difference range corresponds to mere 13%. Differences in cement shares arising from varied concrete mixes, which according to the present study is the main driver of CO_2 emissions, were ignored because most previous assessments have considered a fixed mix composition for a standard block.

Material composition explains between 66 and 99% of CO_2 emissions and between 37 and 95% of the CED. Out of this total, cement explains 62–97% of the CO_2 emissions and 32–88% of CED. Electricity and fuels used in the fabrication processes are also relevant (Table 5). At some plants, transport is also an important impact driver due to large transportation distances.

On average, cement was transported over distances between 3 and 771 km (median is 330 km) and natural aggregates were transported over distances between 0.3 and 280 (median is 26 km), whereas recycled aggregates were transported over distances between 0 and 40 km. However, a weighted average based on the amounts requested from each supplier to manufacture a

Table 5
Participation of transport, energy from factory and materials in the CED and CO_2 emission from production of the analyzed concrete blocks.

	CED	CO_2 emission
Transport	1–29%	0.4–15%
Energy from factory	4–62%	0.3–32%
Materials	37–95%	66–99%
Cement	32–88%	62–97%
Aggregates	5–7%	3–4%

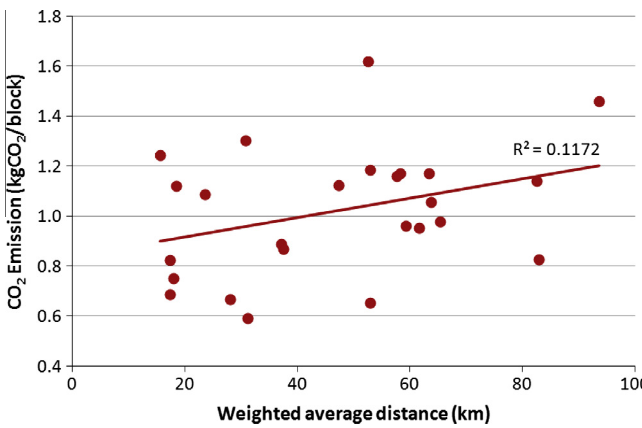

Fig. 2. Relationship between weighted average distance and average CO_2 emission per block.

specific block, yield a range between 16 and 119 km (median is 50 km). Fig. 2 shows that the effect of material transport distances on CO_2 emissions is modest.

3.1. Sources of variability

It is interesting to evaluate the contribution of the range of CO_2 emission factors and CED values adopted for input materials and the uncertainty on the transportation modal on the total variability.

Fig. 3 presents the source of CO_2 emissions and CED variability among the sample, broken down by: (i) uncertainty in materials and transport emission factors; (ii) variable transportation distances and transportation modes; (iii) differences in material inputs adopted by different manufacturers (e.g. cement type), energy consumption, product mass, and mix composition. The later results were assessed based on minimum emission factors and energy consumption values.

Emission factors and energy consumption variability implies 0.17–0.27 $kgCO_2$/block and 0.57–0.83 MJ/block of CED. This translates into 15.3–17.8% of uncertainty in the CO_2 emissions and 7.9–9.4% in CED. Considering that manufacturers use only input materials with lower emission factors and CED, even if the same technological route is considered, CO_2 emissions vary 2.6–3.3 times (Fig. 3a) and CED varies 3.5–4.0 times (Fig. 3b). Uncertainty related to transportation distance and mode differences correspond to 5.4 and 14.4% of the total, which implies in 0.09–0.14 $kgCO_2$/block. The CED uncertainty varies between 3.4–11.6%, which implies in 0.25–1.07 MJ/block.

Variability between minimum and maximum values, considering input materials that present the lower emission and CED values, with or without transport variability is comparable. The assessed sample has shown that material input, mix composition, compaction machine efficiency, and the production system play a more distinct role in the final CO_2 emissions and CED than

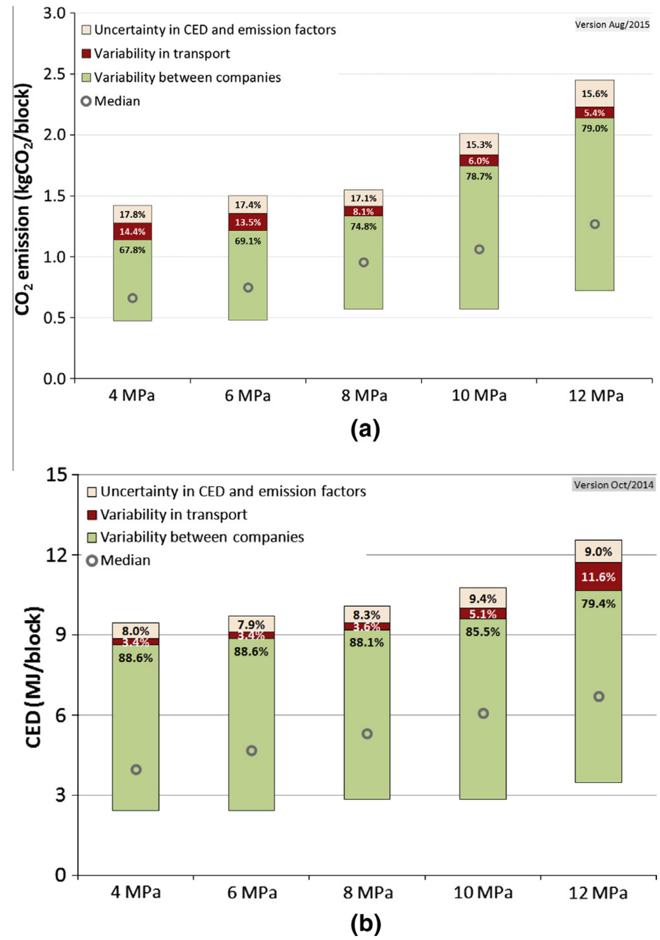

Fig. 3. Ranges and median of CO_2 emissions (a) and CED (b) for concrete block with different strengths of the analyzed companies. Bar colors indicate the contribution of each variability source.

uncertainties in emission factors and variations due to transportation choices.

Block mass is neither statistically correlated to block's CO_2 emissions or CED, which might be explained by the fact that greater cement consumption does not mean greater block mass. CED has a strong relation with CO_2 emissions because the greater energy consumption in cement production, the greater are CO_2 emissions

4. Conclusions

A study of 29 concrete block producers of some Brazilian regions was presented.

The differences between producers that use the same technological route are far from negligible. Considering that manufacturers use only input materials with lower emission factors and CED, CO_2 emissions varies 2.6-3.3 times and CED varies 3.5 to 4.0 times. The large variability due to differences in plant technology denotes the potential of cleaner production initiatives within the sector. It also shows the importance of selecting among suppliers as a mitigation strategy.

Cement was responsible for 62–97% CO_2 emissions and 32–88% of CED. Nevertheless, the clinker fraction of cement was not decisive to control environmental loads, as usually is assumed.

The burden of transporting on the overall impact is between 4 and 14%. Even considering a large country that relies on road transport, the effect of material transportation distances on CO_2 emissions is modest.

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