Life Cycle Impact Assessment of masonry system as inner walls: A case study in Brazil

Karina Condeixa [a,⇑], Assed Haddad [b], Dieter Boer [c]

a Departamento de Engenharia Civil, Universidade Federal Fluminense, Rua Passos da Pátria 156, 3_ andar, Sala 365, Bloco D, São Domingos, 24210-020 Niterói, RJ, Brazil
b Departamento de Construção Civil, Escola Politécnica da Universidade Federal do Rio de Janeiro, Athos da Silveira Ramos, 149, Ilha do Fundão, Centro de Tecnologia, Bloco D, 207, Cidade Universitária, 21.941-909, Rio de Janeiro, RJ, Brazil
c Departament d'Enginyeria Mecanica, Universitat Rovira i Virgili, Av. Paisos Catalans, 26, 43007 Tarragona, Spain

Highlights

- Life cycle impacts of masonry inner walls are assessed.
- A method to estimate building materials demand and waste generation is established.
- The life cycle phase of use present higher impacts than construction and demolition.
- Lime is the highest contributor to radiation, greenhouse and smog.
- Impacts of waste are larger than impact of materials during wall lifespan.

Abstract

The Life Cycle Assessment enables us to determine environmental loads associated to products, processes or activities. This paper uses this methodology to evaluate the impact of inner walls, considering as case study a traditional house in Brazil, made by: ceramic bricks masonry and sand and cement mortar. The impacts are assessed with the CML2001 method for a lifespan of the building of 50 years. Results show which phase has the greatest influence over life cycle impacts, the most impactful material-component, the waste behavior and other peculiarities of life cycle impacts derived from masonry walls. In addition, we created a method for estimating the demand for materials, waste generation and distance traveled in the transportation of materials and waste. This method can assist not only, in environmental assessment, but also in construction and waste management, and policy development.

Keywords: Life Cycle Impact Assessment, Building materials, CML2001, Masonry

1. Introduction

Buildings generate high environmental impacts during all their life cycle [1,2]. The lifespan of the buildings is long and concerns different sectors, activities and stakeholders, which makes their analysis complex [3].

The manufacturing phase embeds the extraction of raw materials, the manufacture of by-products and the transportation to consumers. The extraction of natural resources represents a large impact on scarcity of non-renewable resources [4] while at the same time consumes other resources such as water, electricity or fuel, and also includes dumping waste in the water, air and soil.

As material consumption in construction is large, wrong choices in material specifications, suppliers and constructive technologies, as well as management failures result in a waste of material and handmade and accordingly, in environmental damages and financial losses.

During the use of buildings, natural resources are consumed for building materials substitution in maintenance, remodeling, and extension reforms. Water and energy [5,6] are required for users and equipment's such as Heat-Ventilation-Air Conditioning (HVAC) [7,8]. Solid waste is generated by the partial demolitions, the periodic replacement of building elements like doors, windows, ceramics, metal, and the building materials waste during replacements and extensions [9,10].

During the demolition phase, large amounts of Construction and Demolition Waste (C&DW) are generated, especially if reuse or recycling is not considered [10]. C&DW dumped in landfills becomes useless and obsolete material, while the same natural resources are again extracted from the environment in order to meet the demand of materials.

The transport between extraction, manufacturing, trade, construction and landfill, requires consumption of fossil fuels, thereby depleting non-renewable raw materials and emitting greenhouse gases to the atmosphere [11,12].

The environmental load of buildings concerns impacts linked to activities for building material supply chain, construction, maintenance, waste and transport, yet their impacts are all embedded in the life cycle impacts of the building.

The Life Cycle Assessment (LCA) methodology has been applied to assess potential environmental impacts of products and services throughout their life cycle and has already been reported in studies concerning the building sector. Monteiro and Freire LCA to compare three construction systems of external walls for an English single-family house, evaluating abiotic depletion (CML2001) and resource consumption categories (Ecoindicator99 – EI99), and comparing results of climate change/Global Warming Potential (GWP), acidification and eutrophication [13]. Ortiz et al. evaluated life cycle impacts of building materials and compared three different scenarios for solid waste management: landfilling, incineration and recycling. Eco-efficiency was calculated using the CML2001 method focusing on the aspects of renewable and non-renewable resources, as well as energy and water consumptions [14]. Cuéllar-Franca and Azapagic used LCA to assess the carbon footprint throughout the lifespan (50 years) of three typical types of houses in the United Kingdom. The buildings have different areas: individual (130 m^2), semi-detached (90 m^2) and terraced (60 m^2), and were built with bricks and concrete blocks. They applied CML2001 method through the software GaBi to assess the environmental performance, of the buildings, computing the impacts in global warming for the constructed area of the buildings. The results highlighted the gains in household recycling materials and the importance that decisions taken in the design and construction phases have in the impacts of use and end of life phases [15].

There are many aspects that affect the life cycle impacts of buildings. These aspects must be considered in the planning for the building construction, in use and maintenance and waste management of the building. However, a study that assesses the strengths and weaknesses of each building system would be unprecedented and useful to decision makers involved in the construction sector.

The aim of this study is to analyze internal walls of masonry in order to visualize an overall picture of this construct system. We evaluate the behavior of materials-components and waste of masonry as potential polluter and appraise impacts linked to each phase of the building life cycle. Thereby, we intend to offer data to decision makers so that they can conduct an improvement in new ventures planning.

2. Methodology

The methodology in this study is linked to LCA standards – ISO 14040 series [16,17] and to procedures of CML2001 method [18]. However, some regional differences were considered in selecting data from the LCA database, and in elaborating datasets for calculation. These particularities are explained in detail in the description of model limitations and procedures.

2.1. Life Cycle Assessment

The LCA methodology is guided by the ISO 14040 series, which suggests that the application of LCA is composed of four phases [16,17]:

- Schedule definition and scope – definition of functional units, boundaries of the study, indicators to be used and desired goals;
- Life Cycle Inventory (LCI) – detailed research of the processes, their inputs and outputs;
- Life Cycle Impacts Assessment (LCIA) – application of Impact Assessment Method and calculation of environmental impacts; and

- Analysis and interpretation of results.

2.2. CML2001

CML2001 is an Impact Assessment Method, which has a problem-oriented approach (also called midpoint or impact-oriented) that evaluates impacts for CML2001 characterization factors. Table 1 presents the types of CML2001 characterization adopted in this study and their corresponding scientific unit.

Table 1 - Characterization factor CML2001, adapted from (EcoinventCentre 2013; Sleeswijk & Oers 2008; Leiden Universiteit 2014)

Characterization factor CML2001	Type	Unit
Acidification potential	Generic	kg SO_2-Eq
Climate change	GWP 100a	kg CO_2-Eq
Eutrophication potential	Generic	kg PO_4-Eq
Freshwater aquatic Eco toxicity	FAETP 100a	kg 1,4-DCB-Eq
Freshwater sediment Eco toxicity	FSETP 100a	kg 1,4-DCB-Eq
Human toxity	HTP 100a	kg 1,4-DCB-Eq
Ionizing radiation	Ionizing radiation	DALYs
Land use	Competition	m^2a
Malodours air	-	m^3 air
Marine aquatic Eco toxicity	MAETP 100a	kg 1,4-DCB-Eq
Marine sediment Eco toxicity	MSETP 100a	kg 1,4-DCB-Eq
Photochemical oxidation (summer smog)	Low NOx POCP	kg ethylene-Eq
Resources - depletion of abiotic resources	Depletion of abiotic resources	kg antimony-Eq
Stratospheric ozone depletion	ODP 40a	kg CFC-11-Eq
Terrestrial Eco toxicity	TAETP 100a	kg 1,4-DCB-Eq

2.2.1. Characterization factors CML2001

The characterization factors CML2001 represents impact indicators at ‘‘midpoint level’’ which represent, in simplified form, the type of impact which affect the environment [18]. Table 2 shows the characterization factors CML2001 and the acronyms adopted for them.

Table 2 - Characterization factor CML2001.

Characterization factor CML2001	Acronym
Acidification potential	AP
Climate change	CC
Eutrophication potential	EP
Freshwater aquatic Eco toxicity	FAE
Freshwater sediment Eco toxicity	FSE
Human Toxity	HT
Ionizing radiation	IR
Land use	LU
Malodors air	MA
Marine aquatic Eco toxicity	MAE
Marine sediment Eco toxicity	MSE
Photochemical oxidation	PO
Resources – depletion of abiotic resources	RE
Stratospheric ozone depletion	SOD
Terrestrial Eco toxicity	TE

2.3. Model limitation and implications

For the elaboration of our model, the data of material and waste impacts are retrieved from the EcoInvent database [19]. This data is not specific for the inventories held in our case study and they may not be representative. In order to minimize errors in the final results, we created a dataset for LCA impacts using similar manufacturing, similar destinations to waste and similar vehicles for transport instead of using the market datasets, which are calculated by averaging many countries around the world.

2.4. Procedure

Estimation of material required in the different phases of the life cycle of the building and the distances between the manufacturing-trade-sites and the landfills are calculated. The LCIA is then performed, according to the following steps:

- The building material consumption and C&DW generation are estimated based on technical and academic literature corresponding to Brazil [20–22].

Standard regulation about building performance indicates the lifespan of building elements [23]. It enables the estimation of the frequency of maintenance reforms (e.g. electrical and plumbing) and recast the building (such as changes of plant: revert rooms, create or join rooms).

- The medians of distances between potential suppliers to the construction site are added to the distance between the extraction and the manufacturing suppliers to obtain the total distance traveled by each material.
- Data of CML2001 impact indicators for material and transport are retrieved from the EcoInvent database and adapted to the Brazilian case when possible.
- In the LCIA, all CML2001 impacts are calculated by multiplying the specific impact indicators (data retrieved from EcoInvent for CML2001) by the mass of the corresponding component-material, and by the distance traveled in the transportation of materials to site or in the transportation of waste to inert materials landfills. The total impacts for each of the 14 impact indicators considered are obtained for masonry from the sum all phases: construction, use and demolition. The mathematical presentation is as follow:

Each of the 14 CML2001 characterization factors for material demand of each material-component m of masonry in each phase p is given by,

$$I_{m,p}(factor) = Mass_{m,p}\left(CML_m + CML_t \cdot \frac{D_{m,p}}{1000}\right) \qquad \forall(factor) \qquad (1)$$

Where,

Im,p(factor) = impact of demand of material m in phase p in each CML2001 factor (unit variable, Table 1).
Massm,p = mass of material m in phase p (kg).
CMLm, CMLt = indicators of characterization factors CML2001 for material and transport, respectively (unit variable, Table 1).
Dm,p = distance traveled by materials m between manufacture-trade-construction site in phase p (ton km).

And each of the 14 CML2001 characterization factors for generation of waste w in phase p is given by,

$$I_{w,p}(factor) = Waste_{w,p}\left(CML_w + CML_t \cdot \frac{D_{w,p}}{1000}\right) \qquad \forall(factor) \qquad (2)$$

Where,

Iw,p(factor) = impact of generation of waste w in phase p in each CML2001 factor (unit variable, Table 1).
Massw,p = mass of waste w in phase p (kg).

CMLw, CMLt = indicators of characterization factors CML2001 for waste w and transport, respectively (unit variable, Table 1).
Dw,p = distance traveled by waste w between building site and landfill in phase p (ton km).

Whereas each of the 14 characterization factors CML2001 for masonry in each phase of the building life is given by:

$$I_p(factor) = Mass_{w,p}\ (CML_w + CML_t \cdot \frac{D_{w,p}}{1000}) + \sum_m Mass_{m,p} \left(CML_m + CML_t \cdot \frac{D_{m,p}}{1000}\right) \quad \forall(factor) \qquad (3)$$

Where,

Ip(factor) = impacts in phase p for each factor CML2001 (unit variable, Table 1).

The total impact for each of the 14 characterization factors CML2001 for masonry during walls lifespan is then given by:

$$I_{lc}(factor) = \sum_p I_p \qquad \forall(factor) \qquad (4)$$

Where,

Ilc(factor) = impacts of masonry life cycle into each factor CML2001 (unit variable, Table 1).
Ip = impact of phase p for each factor CML2001 (unit variable, Table 1).

- Finally, the interpretation phase is made with the aim of identifying weaknesses and strengths of the use of masonry walls for dwellings in Brazil from a life cycle viewpoint, comparing the impacts of different materials-components and the amount of material and waste employed.

2.4.1. Remark

Eqs. (1) and (2) can be applied to the calculation of impacts of materials (I_m) and waste (I_w) for all life cycle by replacing the mass of material or waste in a given phase by that of the entire life cycle:

$$I_m(factor) = \left(CML_m + CML_t \cdot \frac{D_{m,p}}{1000}\right) \sum_p Mass_{m,p} \qquad \forall(factor) \qquad (5)$$

$$I_w(factor) = \left(CML_w + CML_t \cdot \frac{D_{w,p}}{1000}\right) \sum_p Waste_{w,p} \qquad \forall(factor) \qquad (6)$$

3. Case study

The object of study is a traditional construction of single family dwelling in Brazil: which inner walls are built by manual application of grout mortar between hollow bricks, lay brick, roughcast, and plaster (handmade at the construction).

3.1. Goal and scope

This study aims to evaluate Life Cycle Impacts of a dwelling in Brazil applying a Life Cycle Assessment approach by following the CML2001 methodology. Particularly, it focuses to evaluate the impact of inner walls of masonry of ceramic brick and cement-sand made mortar.

The functional unit of this study are the inners walls of the house and the boundaries covered from cradle to grave, embedding: extraction, construction, use-maintenance and demolition phases of the buildings. The EcoInvent database provides us LCIA (Life Cycle Impact Assessment) values and along with it, the estimation of building material demand, of waste generation and of the distribution of both was mandatory to adapt the values of LCIA database to our case study. Moreover, CML2001 is the method for impact assess used, considering all its indicators.

3.1.1. Functional unit

The functional unit is defined as the measure applied in evaluating performance of systems or products [16,17,24]. This study adopts a functional unit of 115 m^2 inner wall calculated by multiplying the length by the height of the walls.

3.1.2. Boundary

This research has a perspective from cradle to grave of 50 years building lifetime, including: early stages for building material manufacturing, construction, use/maintenance, demolition, and distribution (transport) from material to site and from waste to landfill.

3.2. Estimating material, waste and distances

The wall area of 115 m^2 is calculated by multiplying by the height of the linear dimensions of the walls. The technical details for the implementation of the wall is based on the composition of the price tables for budgets – TCPO Pini [25] (Table 3).

Table 3 – Technical details

Building elements	Feature	Thickness	Ratio
Mortar			
Lay brick	Between bricks	1.50 cm	1:2:8 (cement:lime:gravel)
Roughcast	Adherence	0.05 cm	1:3 (cement:gravel)
Plastering	Plumb	0.20 cm	1:2:9 (cement:lime:medium sand)
Fine plastering	Preparation for painting	0.15 cm	1:4 (cement:fine sand)
Brick			
Hollow 9x19x29cm	Type of brick laying called "1/2 wall"	9.00 cm	-

The waste of the masonry system is classified by the National Environmental Council [26] as class ‘‘A’’: Reusable or recyclable for use as aggregates for construction activity (such as concrete, mortar, ceramics and soil). However, the recycling of these materials is not a widespread practice in Brazil.

The waste of material for construction is based on the median values found by Formoso [22] and Agopyan et al. [21] (Table 4).

Table 4 - Waste in construction (%)

	I						II	Median
	A	B	C	D	E	Median		
Cement	76.6	45.20	34.31	151.86	112.7	76.6	-	76.6
Sand	27.09	29.73	21.05	109.81	42.19	29.73	-	29.73
Brick	39.90	8.2	35.96	26.50	-	31.23	14.00	22.62
Mortar	103.05	87.50	40.38	152.10	73.24	73.24	72.00	72.62
Mortar wall	-	-	-	-	-	-	102.00	
Mortar floor	-	-	-	-	-	-	42.00	

In Table 4, the values represent the percent of wasted material, as a function of the amount of material beyond that needed for the construction. According to Formoso [22] and Agopyan et al. [20], the waste generated by losses of material in the construction may be higher than the materials actually used. Based on these studies we adopt values for waste generation in construction. Since these studies do not present specific values for lime, we used for lime values of mortar. Table 4 shows the percentages adopted for waste generation by losses of material in construction/reforms, as well as the total material required for the construction.

The Brazilian Performance Standard of buildings NBR 15575-1 suggests that the period of perfect operation of electrical and, hydraulics installations, and wall sealing is three years, and that integrity and sealing of electrical and gas facilities need to be inspected every five years [23,27]. Moreover, the amount of reforms and replenished materials used in was estimated from hypotheses formed by analysis of The Brazilian Performance Standard of buildings. Since we adopted for a lifespan of 50 years for the building, we considered that during this time two large reforms replacing 50% of material and seven small reforms replacing 5% of material would take place (Table 5).

Table 5 – Waste of material

Material	Waste in construction/reforms [%]	Total material required [%]
Sand	30	130
Hydrated lime	73	173
Cement	77	177
Brick	23	123

Unlike many countries, in Brazil the transportation of these materials is done exclusively by freight lorry. Hence the Brazil does not fit into datasets market for Rest of the World (RoW) in the Eco- Invent database, the transportation data for the study were selected separately [28] (Table 6).

Table 6 - Distances traveled to site and to landfill.

	Distance to trade (km)	Distance to site (km)	Distance to landfill (km)	Distance total (km)
Sand	30	15.90	-	45.90
Hydrated lime	40	18.80	-	58.80
Cement	40	17.00	-	57.00
Brick	40	34.00	-	74.00
Waste	0	-	11.15	11.15

Table 7 - Distances travelled between suppliers, site and landfills.

	Supplier/Landfill	Distance to site (km)	Median
Sand	I	13.20	15.90
	II	19.20	
	III	14.70	
	IV	16.90	
	V	15.90	
Hydrated lime	I	18.00	18.80
	II	19.10	
	III	18.80	
	IV	15.60	
	V	18.80	
Cement	I	31.30	17.00
	II	16.50	
	III	17.00	
	IV	19.50	
	V	14.70	
Brick	I	34.00	34.00
	II	75.50	
	III	20.00	
	IV	83.40	
	V	33.30	
Waste	I	9.60	11.15
	II	12.70	

The distance for transportation of materials between manufacturing and the trade is adopted based on the interpretation of literature (Technical Reports and an LCA inventory study [29–35]) (Table 6). Specifically, we adopt the median of the distance between the trade and the site for five likely suppliers of materials, and the median of the distance between two possible receptors of landfill waste (Morro do Céu, in Niterói city and Anaiá, in São Gonçalo city) for waste transportation between site and landfill (Tables 6 and 7).

3.3. Datasets

In this LCIA we retrieve data for materials and transports from those entries in the EcoInvent database (version 3) through the ‘‘Allocation, EcoInvent default’’ method, which incorporates previous emissions associated with by-products in total emissions of a product [36].

The LCIA data for materials and the transports are acquired from EcoInvent separately for the elaboration of a specific dataset for calculation of environmental impacts in Rio de Janeiro (described in Table 8), where the transport of these materials is done by lorries. LCIA data for energy and water are not considered separately, they are both embedded in data for materials production from EcoInvent.

Table 8 - EcoInvent material corresponding to components of masonry.

	Material	**EcoInvent reference**
Construction	Sand	silica sand [kg]
	Transport for sand	transport, freight, lorry, unspecified, GLO [metric ton km]
	Hydrated lime	lime production, hydrated, packed, RoW, [kg]
	Transport for Hydrated lime	transport, freight, lorry, unspecified, GLO [metric ton km]
	Cement	cement production, Portland, RoW, [kg]
	Transport for Cement	transport, freight, lorry, unspecified [metric ton km]
	Brick	brick production, RoW [kg]
	Transport for Brick	transport, freight, lorry, unspecified, GLO [metric ton km]
Demolition	C&DW	inert material landfill construction, RoW [kg]
	Transport	transport, freight, lorry, unspecified, GLO [metric ton km]

4. Results

In order to further understand the environmental impact of the construction considered, the origin of the impacts is analyzed from two viewpoints: the relative contribution of each phase and the relative contribution of the different materials. Besides, a comparison between impacts which can be attributed to either the materials used or the waste generated is also provided.

4.1. Life cycle phases

Fig. 1 shows the % of each characterization factor CML2001 that is attributed to each phase of the life cycle of the dwelling, for masonry. The phase comprising from the extraction of raw materials to the construction of the building is responsible for about 22% of the total impact in most of the characterization factors, whereas the demolition phase is responsible for up to 20% The use phase shows the highest contribution to the factors, especially for those that show lower contribution from the other two phases: IR, PO, TE and SOD.

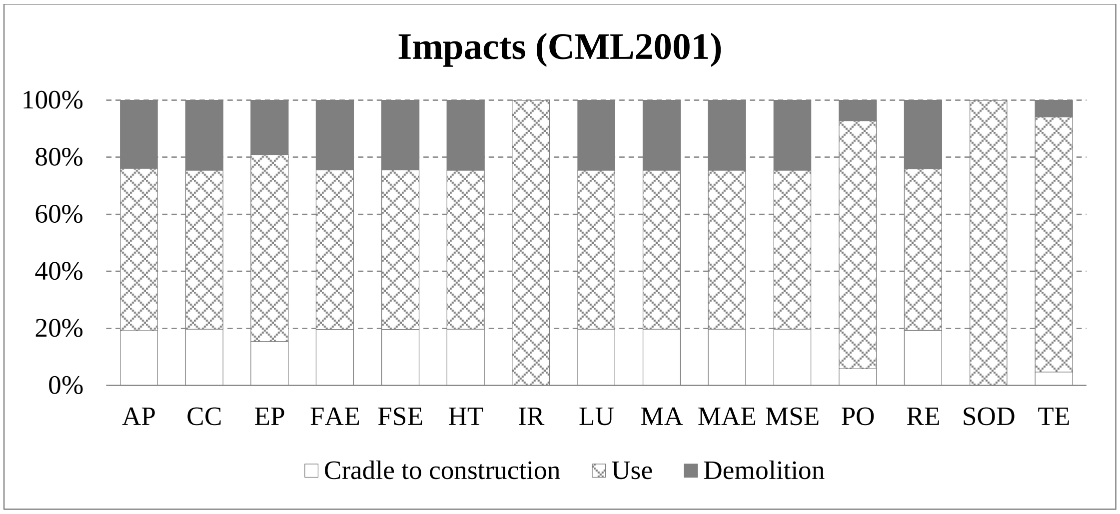

Figure 1- Impacts CML2001 for masonry system

4.2. Materials

Fig. 2 shows the share of each material in the factors CML2001 for masonry walls. The brick is responsible for around 40% of the total impact, with the exception of IR, SOD, PO and TE factors, in which the contribution is lower. The cement contributes 8% except for IR, DB, HT, ET and SOD, to which the contribution is lower. The lime is most relevant for PO, TE, DB, IR, and SOD, especially to the last two factors for which lime are the only material contributing. Finally, the sand has contribution rates of 30% approximately, except for IR, PO, SOD and TE to which its contribution is smaller.

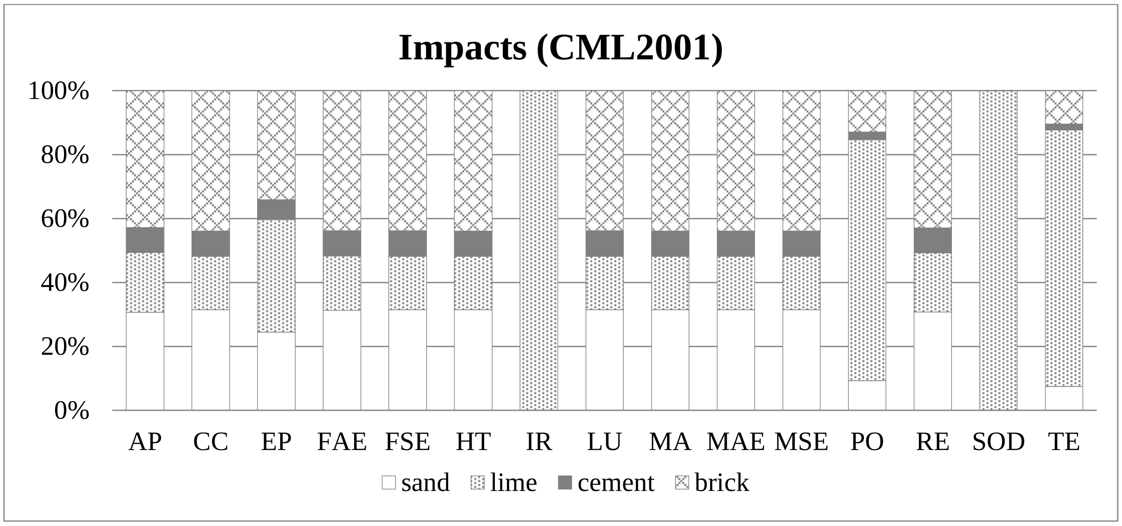

Figure 2 - Impacts CML2001 for material

4.3. Materials vs. waste

The chart below shows the characterization factors for materials demands and waste generation on a logarithmic scale for comparison purposes (Fig. 3). The impacts attributed to materials are similar for most of the factors, being exceptions the LU, MAE and MSE factors. On the other hand, the impacts of waste are fickler, varying significantly between the different factors. The contribution of waste to impacts is only lower than that of materials in IR, SO, and PO factors, whereas it is higher in all other factors and especially in MA.

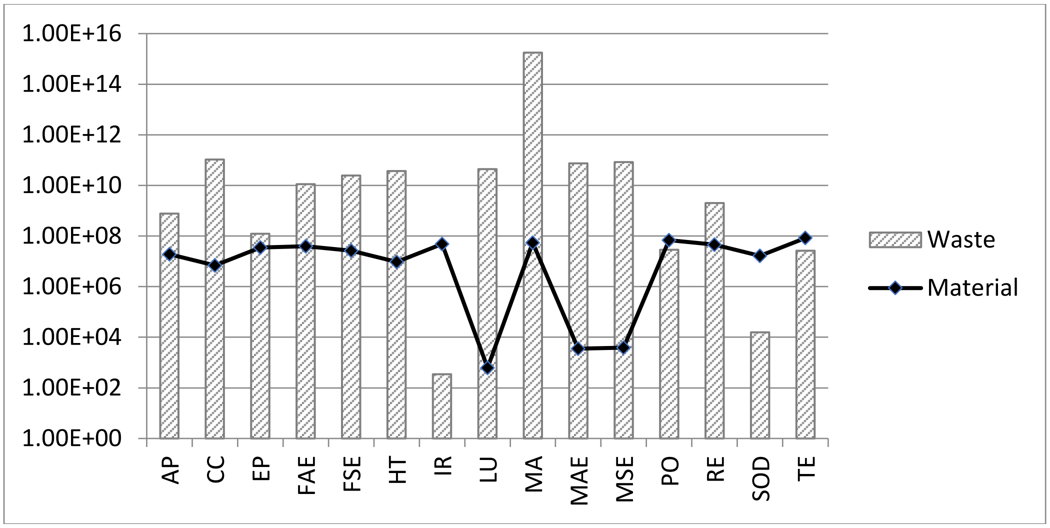

Figure 3 – Impacts for material and for waste

5. Discussion

The use phase is the most impacting phase of the broad lifetime of the building. Recall that over the useful life of the building reforms induce the generation of waste and the use of new materials, what in turn leads to the generation of the associated impacts related with the extraction of raw materials and the transportation of these materials to the manufacturing sites. Moreover, the high demand of material is also due that distinct Brazilian features, such as: the poor qualification of manpower of construction sector, humid climate of Rio de Janeiro which requires constant maintenance of the walls which results in high hate of waste generation, and cultural issues which tend to make many renovations into the buildings, such expansions and changes in disposition of the rooms.

The lime has great impacts on the following factors: ionizing radiation, stratospheric ozone depletion and photochemical oxidation. The radiation comes from the mineral extraction and manipulation, where the use of Personal Protective Equipment (PPE) by workers is strongly recommended since it tends to decrease health problems of employees. Moreover, the depletion of the ozone layer, as well as the photochemical oxidation which is produced by burning fuels in the calcination of the material and the filtering process, can be reduced in the furnace, thus minimizing the emission of these pollutants into the atmosphere. However, we should seek to reduce the use of lime in masonry and search for new alternatives for use as mortar binders.

The waste has severe impact on the malodors air factor, followed by factors such as climate change, land use, marine aquatic eco-toxity, and others. Nevertheless, the comparison between materials and waste showed that the malodorous air is a serious problem for waste generated during the construction and the demolition phases, yet this impact can be mitigated by properly storing the waste and, when possible, by recycling it. The impacts produced by waste outweigh those incorporated by the new materials and, therefore, the recycling of C&DW should be encouraged and efforts should focus on the search of new technologies to increase the lifespan of the materials.

Finally, on the basis of the high demand of materials and high impacts on the waste generated finding, especially during the use phase, it is strongly recommended that action to be taken in order to reduce the amount of materials required and the D&CW generated. The performance of building materials and the stretch of their lifespan could be improvement with actions like qualification of manpower, better planning of construction, improvement of construction and waste management, and recycling of C&DW.

6. Conclusion

This manuscript has addressed an overall picture of impacts of masonry inner walls, considering the characterization factors CML2001 for environmental impacts, according to LCA principles. Since the vehicles used in Brazil for material and waste freight are distinct than those presented in the international database, a proper dataset was created in order to meet the specific regional conditions assuming local suppliers. Results showed that lime is the material-component with a largest contribution to impacts, whereas the use phase is the phases with the highest associated impact. Waste materials show also a higher contribution to impact than new construction materials.

Moreover, we have created a methodology for estimating materials demand, waste generation and distance traveled in freight of materials and waste. This presents a useful tool for environmental assessments, planning, construction and waste management and can also help in the development of policies for the construction industry.

Acknowledgements

The authors would like to acknowledge financial support from the Spanish Government Ministry of Economy and Competitiveness (ENE 2011-28269-C03-03) and from Brazilian Government (Capes – BEX 13846/13-2) as well as, the EcoInvent Centre for the database access for Brazilian academic users.

References

[1] Chang Y, Ries RJ, Wang Y. The quantification of the embodied impacts of construction projects on energy, environment, and society based on I-O LCA. Energy Policy 2011; 39:6321–30.

[2] Li X, Zhu Y, Zhang Z. An LCA-based environmental impact assessment model for construction processes. Build Environ 2010; 45:766–75.

[3] Ortiz O, Bonnet C, Bruno JC, Castells F. Sustainability based on LCM of residential dwellings: a case study in Catalonia, Spain. Build Environ 2009; 44:584–94.

[4] Khasreen MM, Banfill PFG, Menzies GF. Life-cycle assessment and the environmental impact of buildings: a review. Sustainability 2009; 1:674–701.

[5] Broun R, Menzies GF. Life cycle energy and environmental analysis of partition wall systems in the UK. Procedia Eng 2011; 21:864–73.

[6] Tae S, Shin S, Kim H, Ha S, Lee J, Han S, et al. Life cycle environmental loads and economic efficiencies of apartment buildings built with plaster board drywall. Renew Sustain Energy Rev 2011; 15:4145–55.

[7] Blom I, Itard L, Meijer A. LCA-based environmental assessment of the use and maintenance of heating and ventilation systems in Dutch dwellings. Build Environ 2010; 45:2362–72.

[8] Radhi H. On the optimal selection of wall cladding system to reduce direct and indirect CO_2 emissions. Energy 2010; 35:1412–24.

[9] Marinkovic´ S, Radonjanin V, Malešev M, Ignjatovic´ I. Comparative environmental assessment of natural and recycled aggregate concrete. Waste Manage 2010; 30:2255–64.

[10] Coelho A, de Brito J. Influence of construction and demolition waste management on the environmental impact of buildings. Waste Manage 2012; 32:532–41.

[11] Ramesh T, Prakash R, Shukla KK. Life cycle energy analysis of buildings: an overview. Energy Build 2010; 42:1592–600.

[12] Lu Y, Zhu X, Cui Q. Effectiveness and equity implications of carbon policies in the United States construction industry. Build Environ 2012; 49:259–69.

[13] Monteiro H, Freire F. Life-cycle assessment of a house with alternative exterior walls: comparison of three impact assessment methods. Energy Build 2012; 47:572–83.

[14] Ortiz O, Pasqualino JC, Castells F. Environmental performance of construction waste: comparing three scenarios from a case study in Catalonia, Spain. Waste Manage 2010; 30:646–54.

[15] Cuéllar-Franca RM, Azapagic A. Environmental impacts of the UK residential sector: life cycle assessment of houses. Build Environ 2012; 54:86–99.

[16] ISO. ISO 14040 – Environmental Management: Life Cycle Assessment: Principles and Framework. Geneva: ISO; 2006.

[17] ISO. ISO 14044 – Environmental Management – Life Cycle Assessment – Requirements And Guidelines; 2006.

[18] PRè Consultants, Goedkoop M, Oele M, Schryver A de, Vieira M. SimaPro Database Manual Methods library. product ecology consultants; 2008.

[19] EncoinventCentre. Ecoinvent database; 2014.

[20] Agopyan V, Souza UEL, Paliari JC, Andrade AC. Alternatives to reduce the waste of materials at construction sites (in Portuguese). Habitare; 2001. p. 26.

[21] de Souza UEL, Paliari JC, de Andrade AC, Agopyan V. Loss of materials at construction sites: braking the myth (in Portuguese) 2013:5–9.

[22] Formoso C. Losses in construction: concepts, classifications and their role in improving the sector (in Portuguese). SINDUSCON/SP; 1996.

[23] Brazilian Association of Technical Standards-ABNT. NBR15575-1 Residential buildings – Performance – Part 1: General requirements (in Portuguese). Brazilian Association of Technical Standards; 2012.

[24] Blengini GA, Busto M, Fantoni M, Fino D. Eco-efficient waste glass recycling: Integrated waste management and green product development through LCA. Waste Manage 2012; 32:1000–8.

[25] PINI. Composition tables prices for budgets (in Portuguese). 13th ed. São Paulo: Editora PINI Ltda; 2008.

[26] National Environmental Council (Brazil)-CONAMA, Ministry of Environment- MMA. CONAMA Resolution: Resolution existing published between September 1984 and January 2012. Special ed. Brasília; 2012.

[27] Matozinhos R. Manual for use, operation and maintenance of buildings maintenance management system (in Portuguese). Mato Grosso (in Brazil): Edif. Bus. Fair Hous. Constr; 2012.

[28] Spielmann M, Scholz RW. Ecoinvent: services life cycle inventories of transport services background data for freight transport. Int J Life Cycle Assess 2005; 10:85–94.

[29] National Union of the Cement Industry-SNIC. National Union of the Cement Industry 2010 (Brazil); 2010.

[30] Da Silva JO. Mineral Processing. Profile limestone (in Portuguese); 2009.

[31] Brazilian Association of Portland Cement-ABCP. Flowchart of the cement manufacturing (in Portuguese); 2012.

[32] de Almeida SLM, da Luz AB. Manual of aggregates for the construction industry (in Portuguese). Rio de Janeiro: CETEM/MCT; 2009.

[33] Brazilian Service of Support for Micro and Small Enterprises-SEBRAE, College advertising and Marketing-ESPM. Red ceramic: market research (in Portugese); 2008.

[34] Technical Office for Economic Studies Northeast-ETENE. Red ceramic industry report (in Portuguese). Northeast Bank of Brazil S/A; 2010.

[35] Lafontaine M et al. Comparative analysis of the life cycle of walls built with ceramic bricks, concrete blocks and concrete cast in situ (in Portuguese); 2012.

[36] EcoinventCentre. Introduction to EcoInvent Version 3 for Existing Users; 2013.

[37] Sleeswijk A, Oers L van. Normalisation in product life cycle assessment: an LCA of the global and European economic systems in the year 2000. Sci Total 2008.

[38] Leiden Universiteit. CML-IA Characterisation Factors; 2014.