Environmental performance analysis of residential buildings in Brazil using life cycle assessment (LCA)

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HIGHLIGHTS

- Life Cycle Assessment from "cradle to grave" in four typical Brazilian dwellings.
- Assessed global warming, energy demand and other six categories of impact.
- Impact of the operational phase exceeds 80% in several impact categories.
- Foundation, structure, masonry and coating are the most critical subsystems.
- Concrete, ceramic tiles and steel had great contributions in the impacts.

ARTICLE INFO

ABSTRACT

This paper aims to quantify the environmental performance of four typical Brazilian residential buildings with different typologies, through the complete Life Cycle Assessment (LCA) from "cradle to grave". The LCA considers eight impact categories, including carbon emissions and energy demand. Our analysis includes the relative importance of life cycle phases, construction processes and materials that make the largest contributions to the buildings' environmental impacts. According to the results, the operational phase is the most critical, the foundation, structure, masonry and coating have the greatest environmental impacts and in terms of materials, concrete, ceramic tiles and steel made the largest contributions.

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1. Introduction

Building performance is associated with a building's compliance throughout its service life with both pre-established conditions and the functions for which it is designed [1]. Many methodologies and initiatives for building evaluation and certification of buildings have been created, most of these methodologies and initiatives involve devices such as checklists and compliance with requirements [1–3]. However, these methodologies and initiatives do not necessarily ensure the identification of environmental impacts throughout the life of buildings.

The LCA adopts the perspective of evaluating performance and allows analysis of a building's potential impacts throughout the life cycle, along with quantification of the contributions of materials and construction processes and their environmental repercussions [4]. The application of LCA to buildings is a complex process because of their long service life, their use of different materials and construction subsystems, each project's unique traits, the need for maintenance and the influence of user behavior [5,6].

Because buildings consume a great deal of energy during the use and occupation period, many studies have identified the operational phase of the life cycle as the phase with the greatest impact [7–15]. Despite the importance of the use and operational phase, the relevance of the impact generated by building construction cannot be disregarded. Few studies have analyzed the contributions of the construction process and materials in a manner that would enable the identification of critical systems, critical materials, and potential alternatives to reduce the impacts associated with those systems and materials [15–18].

Many LCA studies in buildings prioritize the evaluation of carbon dioxide-equivalent emissions, responsible for Global Warming Potential and the Cumulative Energy Demand [4,15,17,19–21].

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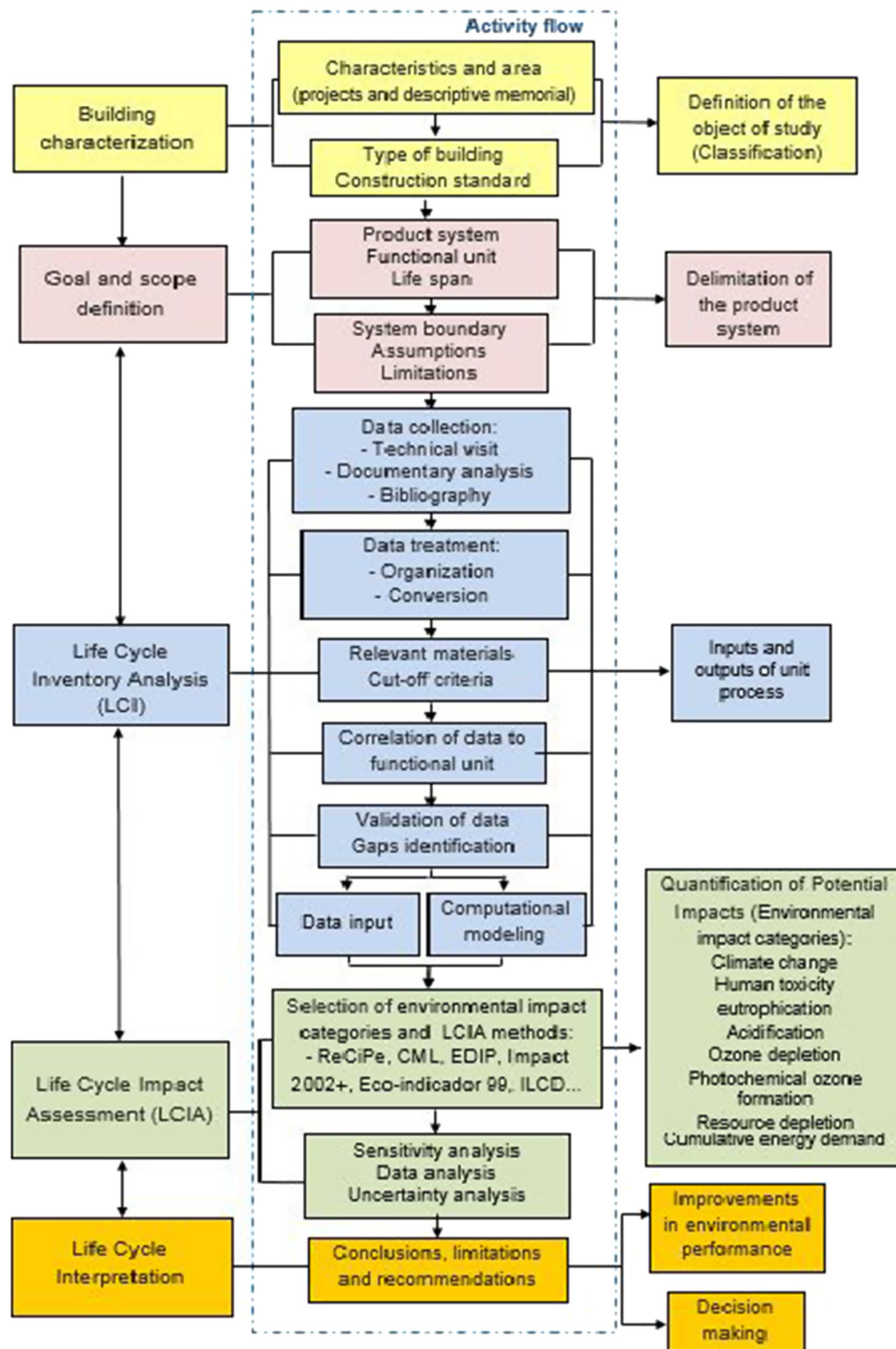
Fig. 1. Flowchart of LCA based environmental performance assessment of residential buildings of Brazil.

Nevertheless, Land Use, Acidification, Eutrophication, Ozone Depletion, Resource Depletion and Human Toxicity are important impacts to be considered [14,22].

Despite the advances in LCA research in civil construction, studies performed in buildings have also presented highly variable results, requiring greater transparency in methodology and data collection and increasing the reliability and repeatability of LCA studies of this type [23]. The absence of methodological structure, common criteria, parameters for construction, transportation, consumption of water and energy, maintenance, waste destination and the practical application of LCA in different regional typologies

represent barriers for the dissemination of this tool [24], as in the case of Brazil. Rare are the LCA studies on buildings in Latin America [21] and considering the significant environmental impacts and Brazil's large housing deficit, estimated at 5.5 million homes [25], it is fundamental to create conditions to disseminate tools that contribute to the evaluation and improvement of the environmental performance of Brazil's residential buildings.

For those reasons, the contribution of this paper is to quantify buildings' environmental performance through examining the methodological structure, local parameters and application of complete LCA to four typical Brazilian residences, assessing asses.

This study also includes evaluation of the relative importance of the impacts of each life cycle phase, along with the identification of the construction processes and materials that make the largest contribution during the construction phase.

2. Methodology

The application of the LCA to Brazilian residential buildings is performed using the flow of activities (Fig. 1), whose structure is based on NBR ISO 14040 [26], NBR ISO 14044 [27] and the Inverted Cone methodology [28].

The Inverted Cone is a methodological approach that guides the data survey and quality improvement process in LCA studies, most notably in the inventory step, in the sense of considering the most relevant data for identifying the environmental impacts of the object of study. Throughout the LCA, this approach recommends assessing the inventoried data's influence on the impacts, allowing efforts related to data collection, treatment and quality improvement to be directed towards their effect on the study's results, aiming at the reduction of uncertainties and the optimization of efforts (Fig. 2).

2.1. Description of the case studies

The LCA was performed in four typical Brazilian residential buildings (Fig. 3), whose main characteristics are summarized in Table 1.

2.2. Application of LCA in the case studies

2.2.1. Building characterization

All of the buildings were qualified as falling within one of Brazil's 12 housing categories, defined as a function of their occupancy characteristics and finishing standards (Table 2).

In addition to supporting the definition of the object of study, this characterization will enable a comparison of similar buildings and the development of Brazilian standards by typology.

2.2.2. Goal and scope definition

This phase corresponds to the LCA study's planning, which defines both the intended application and the product system to be studied.

Therefore, the following was established:

- Goal: This study aims to evaluate the environmental performance of four Brazilian residential buildings by identifying and analyzing potential environmental impacts throughout their life cycle;
- Functional Unit: square meters of total built-up area of the building per year (m^2/year);
- Service Life: 50 years;
- System Boundary: complete LCA divided into 3 phases: pre-operational (raw material extraction, material manufacturing and construction), operational (use and maintenance) and post-operational (end-of-life);
- Impact Categories: Global Warming Potential, Ozone Depletion, Human Toxicity (Cancer effects and Non-cancer effects), Photochemical Ozone Formation, Acidification, Eutrophication (Terrestrial, Freshwater and Marine), Resource Depletion and Cumulative Energy Demand.

Two impact assessment methods were used: (1) the Cumulative Energy Demand (CED) v1.08 for the energy impact; and (2) the International Reference Life Cycle Data System (ILCD 2011) v1.03, midpoint method, recommended by the European Commission
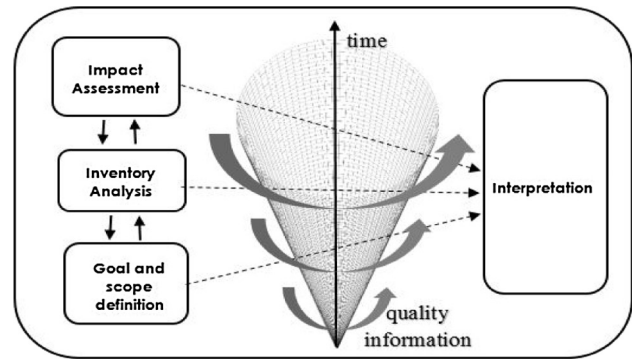

Fig. 2. Inverted Cone Methodology. Source: adapted from [28]

(EC), for the other categories. Both methods are part of SimaPro® 8.0.2, professional version, which was used in this study. The ILCD is a method that results from the analysis of many Life Cycle Impact Assessment (LCIA) methodologies by the Joint Research Center of the EC, whose aim is to reach consensus about the recommended methodology for each environmental issue [30].

2.2.3. Life cycle inventory (LCI)

The survey of the processes' input and output data was performed in relation to the 3 life cycle phases of the studied buildings.

2.2.3.1. Pre-operational phase. This phase included the total mass of the main construction materials and the consumption of water and electric energy during the construction phase. In addition, the direct material losses (solid waste), the transportation of material from the supplier or distribution centers to the construction sites and the waste transportation to the final destination were included.

During the inventory of the pre-operational phase, were defined the flows of materials and the unit processes chosen by the *Ecoinvent* v3.01[1] database. Water and electricity consumption during the construction period was obtained from the bills issued by the suppliers and provided by the construction companies.

With respect to solid waste, the usual theoretical loss were used (Table 3) [31] and applied to the overall values of inventoried construction materials for the quantification of the total mass removed from the construction sites as the result of the materials loss. The need for an estimation of this parameter is caused by the variability of the levels of material loss in Brazil and the lack of control and availability of these values in construction sites.

Table 4 consolidates the distances for the calculation of transportation. When the companies did not provide the values, we estimated the average distances for the transportation of construction materials to the construction sites and for the transportation of solid waste to the final destination. For the waste destination, double the distance was considered because the truck arrives at the construction site empty and returns to the construction landfill.

2.2.3.2. Operational phase. In this phase, the water and electric energy consumption used by home appliances and lighting, the cooking energy and the construction materials required for building maintenance were considered. As in the construction, losses in the form of solid waste generated by the replacement of

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[1] http://www.ecoinvent.org/support/faqs/methodology-of-ecoinvent-3/what-are-global-background-activities-and-where-do-they-come-from.html1

(a) Multi-family dwelling, high-standard (CS1)

(b) Multi-family dwelling, social interest housing (CS2)

(c) Single-family dwelling, high-standard (CS3)

(d) Single-family dwelling, low-standard (CS4)

Fig. 3. Images of the studied buildings.

components in the maintenance process, the transportation of these materials and the generated waste were included.

Energy and water consumption were calculated as a function of average consumption and number of occupants. For monthly electric energy consumption, the Statistical Yearbook of the Energy Research Company [32] was used. For Social Interest Housing (SIH), the average Social Energy Tariff (SET) consumption was obtained from the Brazilian Electricity Regulatory Agency (ANEEL) [33]. With respect to the energy parameters in *SimaPro*®, Brazil's mean voltage matrix available in the *Ecoinvent*® database was used.

For cooking energy, considering that the majority of urban households in Brazil use liquefied petroleum gas (LPG) as energy source for cooking food, LPG consumption data in the residential sector from the National Energy Balance (NEB) [34] were used. For water consumption, the values used by the Water and Sanitation Company of Bahia (EMBASA), the provider of basic sanitation services, were used in the planning to implement and expand those services by typology and income class in Bahia State, Brazil, where the case studies were performed [35,36]. For Social Interest Housing (SIH), single and multi-family dwelling, not included in the data provided by EMBASA, data from local studies were considered [37,38]. The consumption values calculated from these sources for all of Brazil's housing categories and considered in the case studies are presented in Table 5. Although they are considered average data, the consumption profile of the building occupants is known to influence the impacts associated with the use and operational phase.

The quantity of materials used in the maintenance process was estimated from the total values surveyed in the construction phase, resulting in replacement factors [39], i.e., the service life of the project divided by the durability of the construction material, which represents how many times the material is replaced throughout the building's service life (Table 6). Materials with durability greater than 50 years were not considered.

2.2.3.3. Post-operational phase. In this phase, the data for building demolition was calculated. Considering that the majority Brazilian companies sends the construction waste (CW) to landfills, we consider that 100% of the waste went to landfills.

Table 7 presents the consolidated inventory data for the four case studies.

2.2.4. Life cycle impact assessment (LCIA)

The association of the inventoried data with the selected impact categories and the resulting calculation of the indicators of these categories characterize this step. The LCIA was carried out from many analytical perspectives: Overall impact of the complete building, dwelling unit and impact per m²/year; Impact of each life cycle phase: pre-operational, operational and post-operational; Impact of each step of the construction process: Foundation, Structure, Masonry, Coating, Frames, Electrical and Hydraulic Installations and Roofing; Identification of materials that make the largest contribution to the environmental impact of the studied buildings.

2.2.5. Life cycle interpretation

In this step, the obtained results were interpreted, generating input for decision-making and highlighting opportunities to improve the buildings' environmental performance. This analysis considered the type of building, the finishing standard, the construction characteristics and the contribution of the construction subsystems and materials used.

3. Results and discussion

The analyses approach the set of each building's impacts, assessing both the relative participation of the life cycle phases and the contribution of construction subsystems and construction materials.

Table 1
Main characteristics of the case studies.

Housing category	General characteristics	Total area (m²)	No of Units	Dwelling unit area (m²)	Constructive characteristics
CS1 MULTI.16 HS	High-standard multi-family dwelling located in the city of Salvador/BA	10,788	64	115	Metal piles foundation, conventional structure in reinforced concrete, masonry in concrete blocks, walls and ceilings coated with PVA paint, floors and facade in ceramic tiles and gypsum ceilings, concrete gutter and metal roof tile.
CS2 MULTI.5 SIH	Social interest housing (SIH) multi-family dwelling located in the city of Camaçari/BA	57,671	1300	44	Shallow foundation, self-supporting reinforced concrete wall. EPS panel shafts and ceramic blocks in support buildings. Walls coated with gypsum plaster and PVA paint, PVC ceiling cladding and wood structure and ceramic roof tile.
CS3 SIN HS	High-standard single-family dwelling located in the city of Salvador/BA	561	1	561	Shallow foundation, conventional structure in reinforced concrete, masonry in ceramic blocks. Walls and ceilings coated with PVA paint, floors and facade – granite, natural rocks and ceramic tiles and gypsum ceilings cladding. Wood structure and fiber cement roof tiles.
CS4 SIN LS	Low-standard single-family dwelling, located in the city of Feira de Santana/BA	56	1	56	Shallow foundation, conventional structure in reinforced concrete, masonry in concrete blocks. Walls and ceilings coated with PVA paint, ceramic tile floors and gypsum ceilings cladding. Wood structure and ceramic roof tiles

Table 2
Brazilian housing categories– Classification. Source: adapted from NBR 12,721:2006 [29].

Brazilian housing categories			Abbreviation
Single-family dwelling (SIN)	Popular – Social Interest Housing (SIH)		SIN SIH
	Low-standard		SIN LS
	Average standard		SIN AS
	High-standard		SIN HS
Multi-family dwelling (MULTI)	5-floor	Popular (SIH)	MULTI.5 SIH
		Low-standard	MULTI.5 LS
		Average standard	MULTI.5 AS
	8-floor	Low-standard	MULTI.8 LS
		Average standard	MULTI.8 AS
		High-standard	MULTI.8 HS
	16-floor	Average standard	MULTI.16 AS
		High-standard	MULTI.16 HS

Table 3
Usual theoretical loss levels for construction materials. Source: evangelista [31].

Material	Usual theoretical loss (%)
Concrete, steel, mortar plastering, PVC pipes, glass, electrical conduits	5
Hollow structural blocks, concrete blocks, ceramic tile	8
Sealing blocks, solid structural blocks, roof tiles, cement, lime, sand, laying mortar, gravel, gypsum, wires and cables	10
Wood	15

3.1. Environmental impacts of the case studies

As expected, the high-standard dwellings presented the largest environmental impacts due to their larger area, average population and consumption profile compared to the low-standard dwellings. In relation to the energy demand (CED), the impact of high-standard dwellings was 2.4 and 4.3 larger when compared to the low-standard multi and single-family dwelling buildings, respectively (Table 8). It should be highlighted that unlike the multi-family dwelling, the single-family dwellings do not share common areas, construction systems or elements like the foundation, structure and roofing.

The high-standard single-family dwelling (CS3) had the largest environmental impact of all of the case studies, primarily because its expressive built-up area is about 5 times larger than the multi-family dwelling of the same standard (CS1) and 10 times larger than the low-standard single-family dwelling (CS4). Taking this building as a reference, a relative comparison of its environmental impact and those of the other case studies was performed (Fig. 4). The biggest generator position of the high-standard dwelling units (CS1 and CS3) was reinforced and the prevalence of the impacts by single-family dwellings was verified when compared to multi-family dwellings.

From another analytical perspective, when using the functional unit of m²/year, the order of relevance of the results from the case studies changes. Both the low-standard dwellings (CS2 and CS4), which have smaller built-up areas, had the highest environmental impact per unit of area, except in the Resource Depletion category, in which CS3 had the largest impact because of its significant built-up area and consumption of a large amount of material/m² (Table 9). From the perspective of evaluation per m2/year, the reference (100%) for the relative comparison of the generated

Table 4
Transportation parameters used in the case studies.

No	Housing category	Life cycle phase	Material	Distance supplier/Construction site	Distance construction site/Landfill
			Transportation parameters – Case studies (CS)		
CS1	MULTI.16 HS	Construction	Cement	50 km	–
		Construction	Ceramic tile	50 km	–
		Construction	Other materials	15 km	–
		Maintenance	Replacement materials	15 km	–
		All phases	Solid waste disposal	–	25 km × 2 = 50 km
CS2	MULTI.5 SIH	Construction	Cement and ceramic tile	32 km	–
		Construction	Ceramic block	78 km	–
		Construction	Other materials	15 km	–
		Maintenance	Replacement materials	15 km	–
		All phases	Solid waste disposal	–	15 km × 2 = 30 km
CS3	SIN HS	Construction	Cement	50 km	–
		Construction	Ceramic tile	56 km	–
		Construction	Other materials	15 km	–
		Maintenance	Replacement materials	15 km	–
		All phases	Solid waste disposal	–	15 km × 2 = 30 km
CS4	SIN LS	Construction	Cement	70 km	–
		Construction	Ceramic tile	100 km	–
		Construction	Ceramic roof tile	80 km	–
		Construction	Other materials	15 km	–
		Maintenance	Replacement materials	15 km	–
		All phases	Solid waste disposal	–	15 km × 2 = 30 km

Table 5
Parameters of the use and operational phase – Case study.

Type	Classification	Average population	Type of tariff	Electric energy (kWh/month)	Cooking energy (kg GLP/month)	Water (m^3/month)	Case study
				Housing categories of Brazil – Parameters of consumption (dwelling unit)			
				Average consumption			
Single-family dwelling (SIN)	Popular (SIH) – SIN SIH	3	Social tariff	130	7,2	9	–
	Low-standard – SIN LS	3	Average	174	7,2	11	CS4
	Average standard – SIN AS	4	Normal	279	9,6	23	–
	High-standard – SIN HS	4	High	419	9,6	37	CS3
Multi-family dwelling (MULTI)	Popular (SIH) - MULTI.5 SIH	3	Social tariff	108	7,2	10	CS2
	Low-standard – MULTI.5 LS	3	Average	145	7,2	12	–
	Average standard – MULTI.5 AS	4	Normal	233	9,6	28	–
	Low-standard – MULTI.8 LS	3	Average	174	7,2	12	–
	Average standard – MULTI.8 AS	4	Normal	271	9,6	28	–
	High-standard – MULTI.8 HS	4	High	349	9,6	33	–
	Average standard – MULTI.16 AS	4	Normal	310	9,6	28	–
	High-standard – MULTI.16 HS	4	High	388	9,6	33	CS1

environmental impacts is the building, which had the highest impact in each category (Fig. 5).

By evaluating the cumulative energy demand, the case study with the largest energy impact per m^2/year was the low-standard single-family dwelling (CS4), followed by the low-standard multi-family dwelling (CS2), high-standard multi-family dwelling (CS1) and high-standard single-family dwelling (CS3). Dwellings with smaller areas concentrate more people per m^2, contributing to higher relative water and energy consumption throughout its 50 years of service life. Therefore, the low-standard dwellings have a larger impact than those of the high-standard dwellings, which, despite their larger absolute population, have lower occupant density (persons/built-up area of dwell-

ing) and consequently, a more broadly distributed impact per m^2. Many LCA studies use the functional unit of impact per m^2/year to compare different typologies and service lives. However, caution is recommended to select an adequate functional unit because dwelling units with lower impacts per m^2 may present the highest results when the impact of the dwelling unit is considered.

3.2. Impacts of life cycle phase

The operational phase is responsible for the largest part of the environmental impacts by the buildings (Table 10).

This scenario is primarily due to energy consumption in the use phase, along with the demand for water and the construction

Table 6
Replacement factors – Maintenance. Source: adapted from tavares [39].

Material	Building service life (years)	Material durability (years)	Replacement factors
Frames, doors and windows	50	46	1,09
PVC pipes	50	45	1,11
Copper pipes	50	42	1,18
Steel metal tile	50	38	1,31
Wiring, switches and sockets	50	38	1,31
Ceramic tile, grout and mortar	50	30	1,68
Galvanized iron pipe	50	18	2,78
Painting materials	50	12	4,17

materials used to maintain the buildings throughout 50 years. As observed, the higher the demand for materials in the construction phase – as in the case study 3 – the larger is the contribution of this life cycle phase and consequently, higher is the balance of the impact between the pre-operational and operational phases. The post-operational phase had little relevance (0–6%).

3.3. Impacts of the construction process

We also evaluated the contribution of each step of the construction process in the buildings environmental impacts. The impacts by water and energy consumption during construction were also presented and these obtained low impact in all categories evaluated.

Table 7
Consolidated inventory – Case studies – Total building consumption.

Consolidated inventory – Case studies							
Description	CS1 MULTI.16 HS		CS2 MULTI.5 SIH		CS3 SIN HS		CS4 SIN LS	
I. Pre-operational phase – Construction	Total for the building		Total for the building		Total for the building		Total for the building	
Step of the construction process:	Input	Waste	Input	Waste	Input	Waste	Input	Waste
Foundation (kg)	684,185	34,209	11,232,675	578,565	142,240	9,534	23,522	1,476
Structure (kg)	220,838	12,467	43,982,252	2,199,113	204,321	13,368	12,307	700
Masonry (kg)	2,748,465	231,420	81,470	8,145	93,248	9,469	23,816	1,985
Coating (kg)	899,515	83,554	3,384,480	249,419	128,288	11,985	21,598	2,104
Frames (kg)	24,300	745	159,809	3,035	2,133	92	154	6
Hidraulic installations (kg)	23,524	1,088	149,589	4,447	400	19	129	5
Electrical installations (kg)	815	56	2,778	258	59	4	164	8
Roofing (kg)	92,562	6,651	2,049,921	188,686	15,074	1,199	5,000	458
Transportation (truck):								
3.5–7.5 ton (t.km)	703	–	989	–	143	–	12	–
7.5–16 ton (t.km)	23,162	18,510	844,341	96,950	3,723	1,370	445	202
16–32 ton (t.km)	56,280	–	93,776	–	6,707	–	1,351	–
Consumption during construction phase:								
Water (m^3)	6,745	–	17,800	–	300	–	52	–
Electricity (kWh)	85,094	–	385,900	–	4,663	–	283	–
II. Operational phase – Use and maintenance								
Replacement material (kg)	410,097	26,889	1,878,439	127,720	33,487	2,538	2,395	173
Transportation (truck):								
3.5 – 7.5 ton (t.km)	7,496	–	28,177	3,832	502	76	36	5
Electric Energy – Kwh (50 years)	14,881,725	–	84,204,970	–	251,129	–	104,637	–
Cooking Energy – kg LPG (50 years)	368,640	–	5,616,000	–	5,760	–	4,320	–
Water – m^3 (50 years)	1,248,860	–	8,101,080	–	21,983	–	6,769	–
III. Post-operational phase – End-of-life								
Total Incorporated Mass (kg)	–	4,707,220	–	59,562,025	–	571,042	–	82,169
Transportation (truck):								
7.5–16 ton (t.km)	–	235,361	–	1,786,861	–	17,131	–	2465

Table 8
Environmental impact per dwelling unit – Case studies.

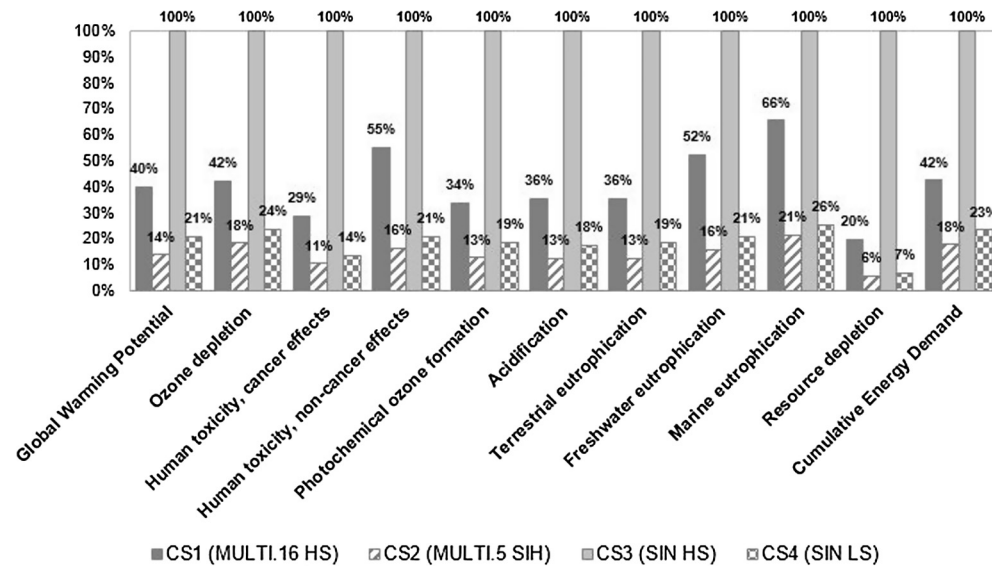| Impacts per dwelling unit – Case studies						
Impact category	Abbreviation	Indicator	CS1 (MULTI.16 HS)	CS2 (MULTI.5 SIH)	CS3 (SIN HS)	CS4 (SIN LS)
Global warming potential	GWP	kg CO$_2$ eq	121,767	42,317	304,791	64,222
Ozone depletion	OD	kg CFC-11 eq	0.0054	0.0023	0.013	0.003
Human toxicity, cancer effects	HT-c	CTUh	0.0084	0.0031	0.029	0.004
Human toxicity, non-cancer effects	HT-n	CTUh	0.0669	0.0198	0.121	0.025
Photochemical ozone formation	POF	kg NMVOC eq	354	135	1,052	196
Acidification	AP	Molc H + eq	696	244	1,950	341
Terrestrial eutrophication	EP-t	Molc N eq	1,306	464	3,659	689
Freshwater eutrophication	EP-f	kg P eq	50	15	96	20
Marine eutrophication	EP-m	kg N eq	498	163	759	194
Resource depletion	RD	kg Sb eq	14	4	73	5
Cumulative energy demand	CED	GJ	1,464	616	3,447	810

Fig. 4. Comparison of the impacts of case studies per dwelling unit in relation to the high-standard single-family dwelling (CS3).

Table 9
Environmental impacts per m²/year – Case studies.

Impact category	Abbreviation	Indicator	CS1 (MULTI.16 HS)	CS2 (MULTI.5 SIH)	CS3 (SIN HS)	CS4 (SIN LS)
		Impacts per M²/year – Case studies				
Global warming potential	GWP	kg CO_2 eq	14	19	11	23
Ozone depletion	OD	kg CFC-11 eq	0.000001	0.000001	0.0000005	0.000001
Human toxicity, cancer effects	HT-c	CTUh	0.000001	0.000001	0.0000010	0.000001
Human toxicity, non-cancer effects	HT-n	CTUh	0.000008	0.000009	0.0000043	0.000009
Photochemical Ozone formation	POF	kg NMVOC eq	0.042	0.06	0.038	0.07
Acidification	AP	Molc H+ eq	0.083	0.11	0.070	0.12
Terrestrial eutrophication	EP-t	Molc N eq	0.155	0.21	0.130	0.25
Freshwater eutrophication	EP-f	kg P eq	0.006	0.007	0.003	0.01
Marine eutrophication	EP-m	kg N eq	0.059	0.07	0.027	0.07
Resource depletion	RD	kg Sb eq	0.002	0.002	0.003	0.002
Cumulative energy demand	CED	GJ	0.174	0.28	0.123	0.29
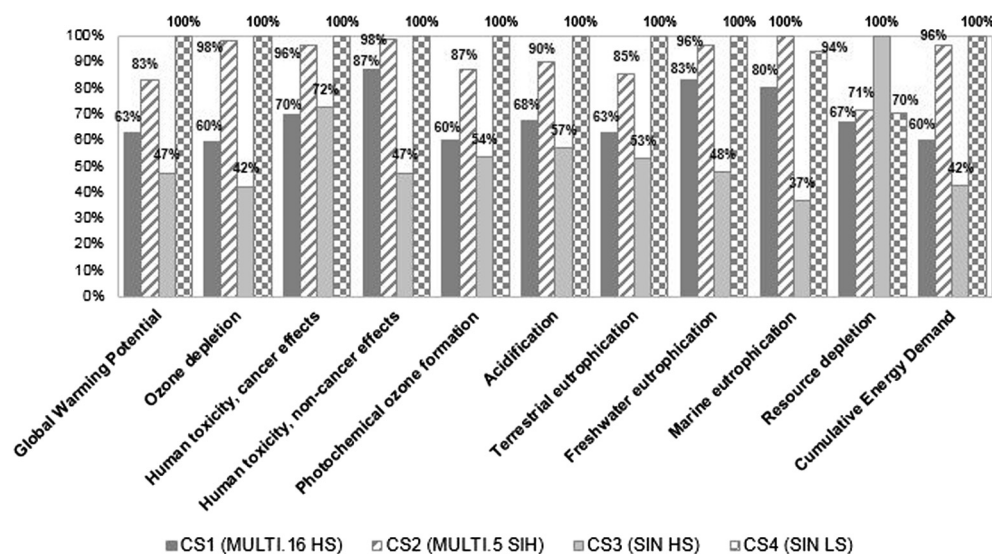
Fig. 5. Comparison of the impacts of case studies per m²/year in relation to the highest-impact building in the category.

Table 10
Impacts by life cycle phase – Case studies.

Impact category	CS1 MULTI.16 HS (%)			CS2 MULTI.5 SIH (%)			CS3 SIN HS (%)			CS4 SIN LS (%)		
	Pre Op.	Op.	Post Op.	Pre Op.	Op.	Post Op.	Pre Op.	Op.	Post Op.	Pre Op.	Op.	Post Op.
Global warming potential	19	80	1	29	70	1	54	44	2	33	65	2
Ozone depletion	15	83	2	14	84	2	44	51	5	20	77	3
Human toxicity, cancer effects	23	77	0	37	62	1	64	35	1	40	59	1
Human toxicity, non-cancer effects	13	87	0	14	86	0	36	63	1	17	82	1
Photochemical ozone formation	25	72	3	32	64	4	57	37	6	38	57	5
Acidification	22	77	1	29	69	2	55	42	3	33	65	2
Terrestrial eutrophication	24	73	3	31	65	4	55	39	6	38	57	5
Freshwater eutrophication	13	87	0	16	84	0	39	60	1	19	81	0
Marine eutrophication	6	93	1	8	91	1	24	73	3	12	86	2
Resource depletion	45	55	0	46	54	0	51	49	0	48	51	1
Cumulative energy demand	16	83	1	17	81	2	46	50	4	22	75	3

Pre Op. = Pre-operational phase; Op. = Operational Phase; Post Op. = Post-Operational Phase.
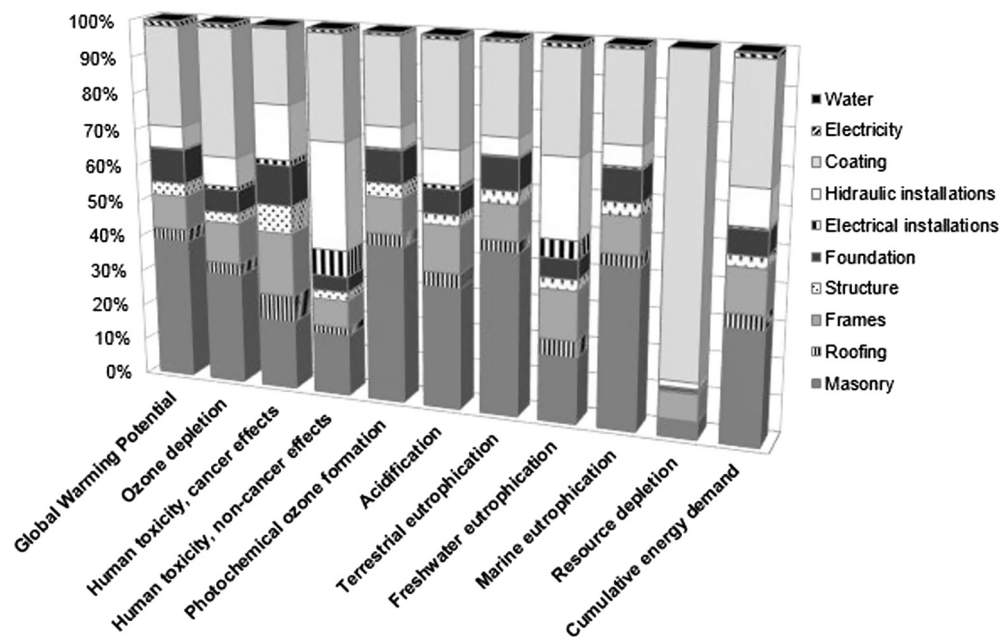
Fig. 6. Impacts per step of the construction process – CS1.
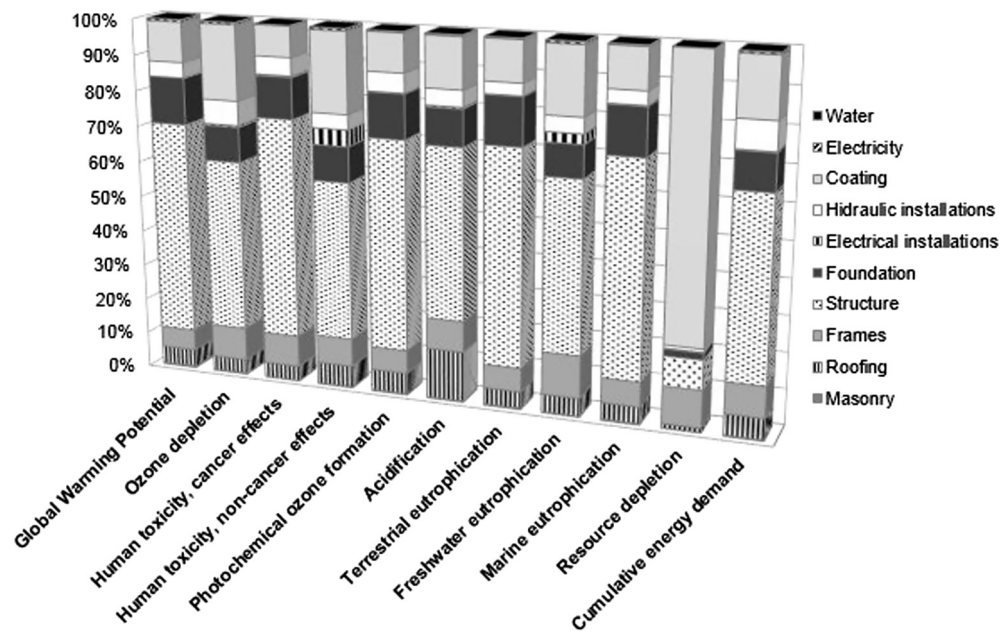
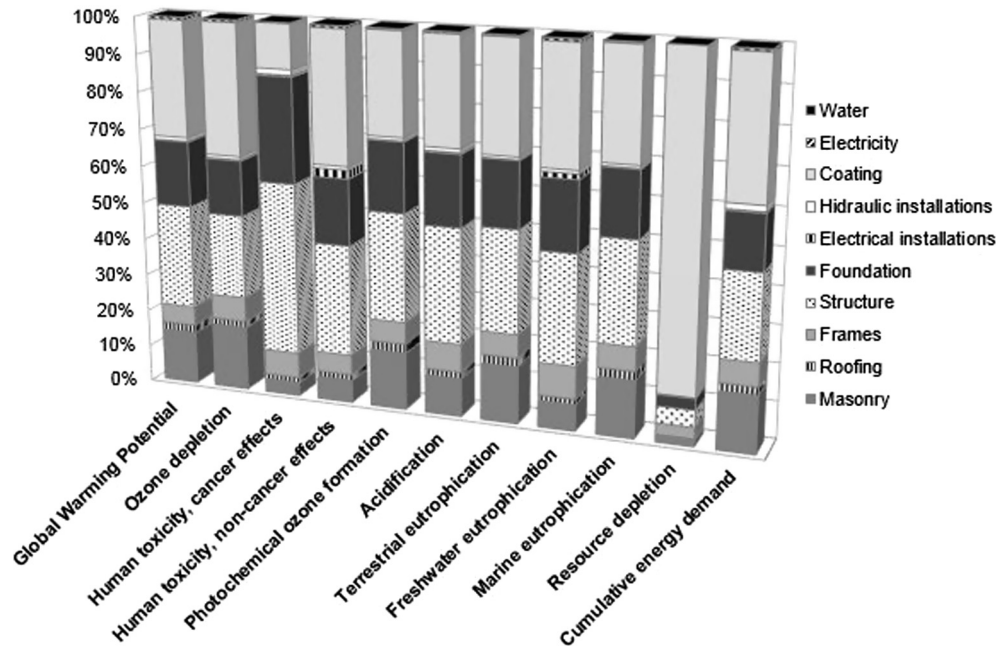**Fig. 7.** Impacts per step of the construction process – CS2.

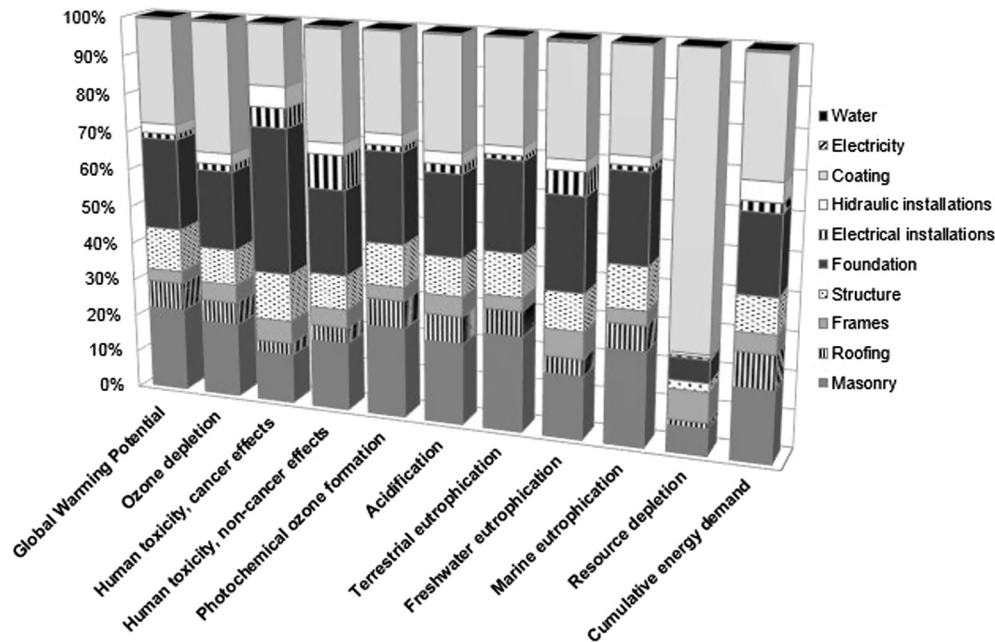**Fig. 8.** Impacts per step of the construction process – CS3.

Fig. 9. Impacts per step of the construction process – CS4.

In CS1 (high-standard multi-family dwelling), the masonry, hydraulic installations and coating had the largest impacts (Fig. 6).

Masonry made the largest contributions, because of concrete blocks, in Global Warming Potential, Photochemical Ozone Formation, Acidification and Terrestrial and Marine Eutrophication. Because of the intensive use of ceramic materials, coating had the largest impacts in the categories of Human Toxicity – cancer effects, Freshwater Eutrophication and Resource Depletion. Hydraulic installations had a large impact in Human Toxicity – non-cancer effects.

Because of study 2's (social interest multi-family dwelling) construction characteristic of self-supporting walls with both struc-

tural and fence functions, the structure made the largest contributions, followed by the coating. Because of the structure's high concentration of concrete and steel, it had the largest impacts in almost all categories, with contributions ranging from 44 to 61%. Because of their use of ceramic materials, coating had the largest impact in Resource Depletion, with 77% participation (Fig. 7).

In CS3 (single-family dwelling), the structure and the coating were associated with the largest impacts because of the characteristics of a high-standard residence with large built-up area and many elements used for the finishing. The structure had the largest impact in Human Toxicity – cancer effects, Photochemical Ozone Formation and Acidification. In turn, the impact of coating stood
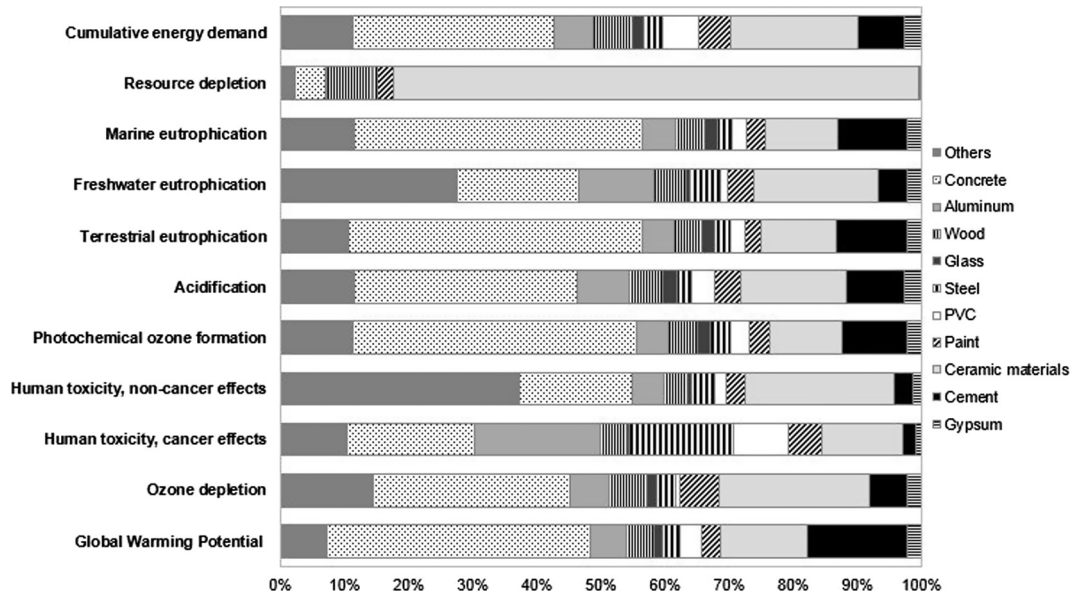
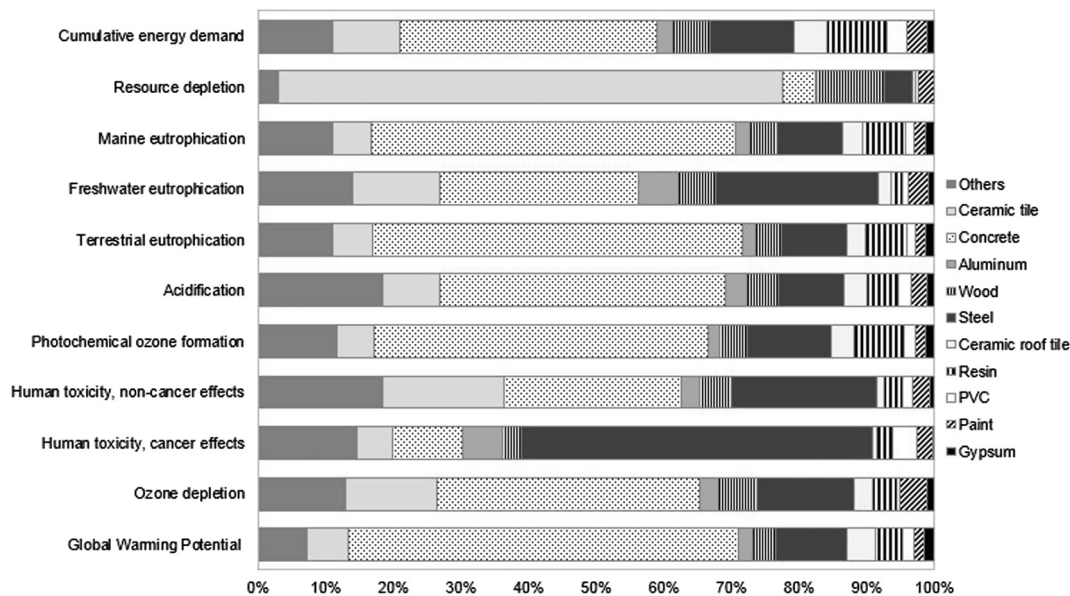**Fig. 10.** Impacts of the construction materials– CS1.

Fig. 11. Impacts of the construction materials – CS2.

out in five categories: Global Warming Potential, Ozone depletion, Human Toxicity – non-cancer effects, Terrestrial, Freshwater and Marine Eutrophication and Resource Depletion (Fig. 8).

In CS4, popular single-family dwelling, the foundation, coating and masonry made the largest contributions in environmental impacts. The foundation stood out in the Human Toxicity – cancer effects and coating, with its ceramic elements and mortar, made the greatest impact of the other evaluated categories (Fig. 9).

In all of the buildings, the coating stands out the major contributor of the generated impacts, most notably because of the use of ceramic materials in the floors, walls and facades, which favor the maintenance process given that they may be replaced once during the building's 50-year life cycle. However, these materials increase the impact generated in the construction phase.

3.4. Impacts of the construction materials

The contribution of the construction materials in the buildings environmental impacts was evaluated. This analysis was made for all materials included in the inventory of the pre-operational phase. For all case studies, the critical materials identified correspond to the critical step of the construction process identified above.

In CS1, the concrete and ceramic materials (ceramic tile and sanitary ceramic) stand out as the largest contributors to the environmental impacts. The first one included the mass of concrete and blocks manufactured with this material, making the largest contribution in the categories of Global Warming Potential, Ozone Depletion, Photochemical Ozone Formation, Acidification Terrestrial and
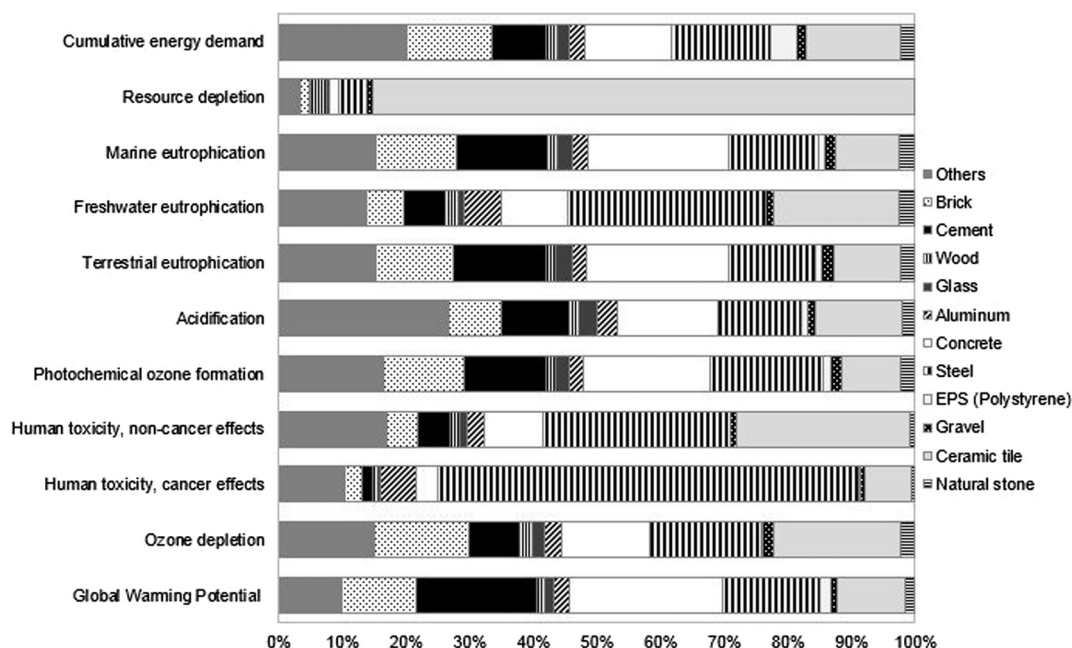
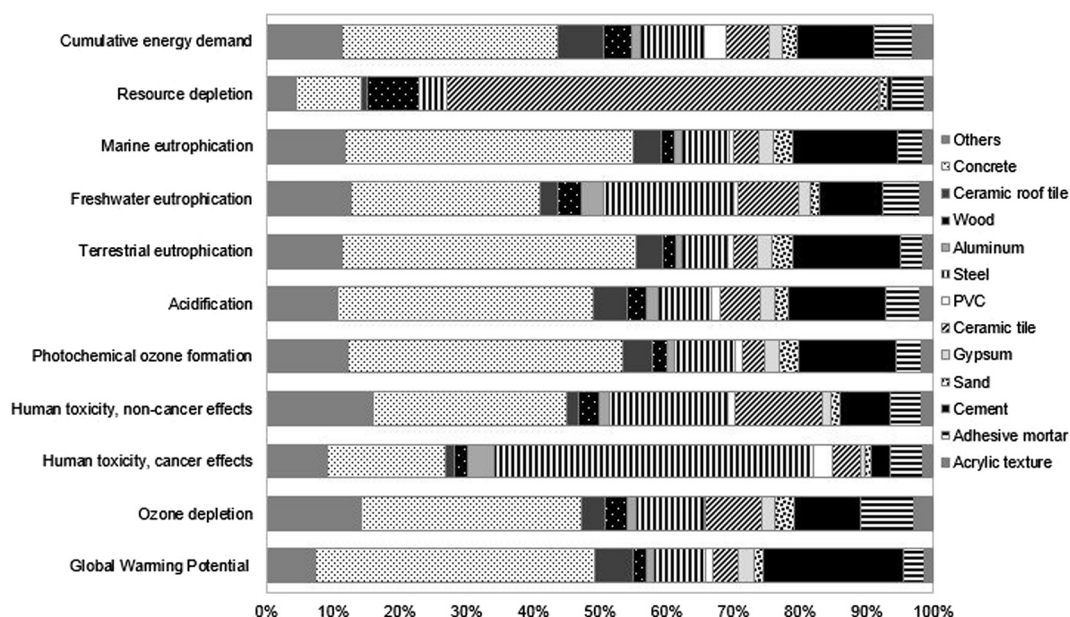**Fig. 12.** Impacts of the construction materials – CS3.

Fig. 13. Impacts of the construction materials – CS4.

Marine Eutrophication and Cumulative Energy Demand. In the Human Toxicity – cancer effects category, aluminum and concrete had equal impact; in turn, ceramic materials were associated with the highest impact on Resource Depletion because of the high demand for the extraction of clay raw material to manufacture it (Fig. 10).

In CS2, CS3 and CS4, the significant impacts of concrete and ceramic materials (tile, roof tile and sanitary ceramic) occurs again, and steel stands out in these three studies. In case studies 2 and 4, both involving low-standard buildings, concrete presented the same behavior, making the largest contributions in all impact categories, except for Human Toxicity – cancer effects, where the steel had the largest impact and in Resource Depletion, where ceramic materials, especially those used in coating, made the largest contri-

bution. In case study 3, concrete was associated with the largest impacts in the categories of Global Warming Potential, Photochemical Ozone Formation, Terrestrial and Marine Eutrophication. Steel had the largest impacts in Human Toxicity – cancer effects and in Freshwater Eutrophication. The ceramic tiles stood out in the Ozone depletion, Human Toxicity – non-cancer effects and Resource Depletion (Figs. 11–13).

4. Conclusions

In LCA studies on buildings is recommended the use of multiple perspectives to analyze the results. This multiple assessment allows us to observe that buildings' impacts vary according to

the size, standard, building characteristics, number of occupants, construction systems and materials.

The single-family dwelling had a higher impact than the multi-family dwellings of the same standard. The same is true of the high-standard dwellings compared to the low-standard dwellings because of their larger areas, number of occupants and consumption profile.

The operational phase is the most relevant because of the significant electric and cooking energy consumption, contributing more than 80% in many impact categories. However, this phase may vary in function of consumption profile. The larger the built-up area and the consumption of construction material, the more significant the pre-operational phase. The post-operational phase had little relevance in all case studies, with contributions of less than 6%.

The contribution analysis of the construction process indicated that the architectural project and the construction system influenced the subsystems with the highest impacts. In the multi-family dwelling units, the masonry and coating presented the greatest impacts, given that many dwelling units share the foundation and structure. The exception occurred for self-supporting structures, where this subsystem stands out from the others. In single-family dwellings, foundation, structure, masonry and coating are the subsystems that have the greatest environmental impacts.

According to the contribution analysis of the main construction materials, concrete, steel and ceramic tiles had the highest environmental impact, with repercussions for the structure, masonry and coating subsystems.

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