Life cycle assessment application in the optimum design of reinforced concrete structures

Aplicação da avaliação do ciclo de vida na otimização de projetos de concreto armado

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Abstract

The objective of this research was to evaluate the use of the Life Cycle Assessment methodology to assist decision-making in structural projects of reinforced concrete. Were studied structural models for an eight-story building, with classes of compressive strength (fck) of concrete ranging from 25 to 50 MPa. Also, were evaluated changes in the dimensions of structural elements, as well as the consumption of component materials of the structure. Results showed that the structural models for classes C40 obtained the best results for 67% of the categories of potential impacts assessed, with potential impact values ranging from 7.4% to 21.2%, including the possibility of saving 18 thousand kg of CO2 emitted. After carrying out an economic analysis, was observed that the structural model for the C40 concrete presented the optimal environmental-economic solution. The results of this research indicate the feasibility of using the Life Cycle Assessment methodology and economic analysis as tools to assist in decision-making during the design process of reinforced concrete structures.

Keywords: Reinforced concrete structure. Life cycle assessment. Structural design. Environmental performance of structures.

Resumo

O objetivo desta pesquisa foi avaliar a utilização da metodologia de Avaliação do Ciclo de Vida para auxiliar a tomada de decisão em projetos estruturais de concreto armado. Foram estudados modelos estruturais para um edifício de oito pavimentos, com classes de resistência à compressão (fck) do concreto variando de 25 a 50 MPa. Também foram avaliadas alterações nas dimensões dos elementos estruturais, bem como o consumo de materiais componentes da estrutura. Os resultados mostraram que os modelos estruturais para as classes C40 obtiveram os melhores resultados para 67% das categorias de potenciais impactos avaliados, com valores de potenciais impactos variando de 7,4% a 21,2%, incluindo a possibilidade de economizar 18 mil kg de CO2 emitido. Após a realização de uma análise econômica, observou-se que o modelo estrutural para o concreto C40 apresentou a solução ambiental-econômica ótima. Os resultados desta pesquisa indicam a viabilidade da utilização da metodologia de Avaliação do Ciclo de Vida e da análise econômica como ferramentas para auxiliar na tomada de decisão durante o processo de projeto de estruturas de concreto armado.

Palavras-chave*: Estrutura de concreto armado. Avaliação do ciclo de vida. Projeto estrutural. Desempenho ambiental de estruturas.*

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Introduction

The construction industry contributes strongly to global economic development and the generation of potential environmental impacts. The sector uses around 50% of all the raw materials consumed in the world, 70% of which are non-renewable. Moreover, 40% of all solid waste generated comes from civil construction, in addition to being responsible for 30% of the greenhouse gases emitted (DIVANDARI; NAJARI, 2016; YAVARI *et al.*, 2017; ALMIRALL *et al.*, 2019; GHAYEB; RAZAK; SULONG, 2020). Therefore, the construction industry faces the challenge of implementing a sustainable model in all its processes, from the efficient use of resources to the incorporation of less polluting materials, creating more environmental-friendly projects (LASVAUX *et al.*, 2015; FERREIRO-CABELLO *et al.*, 2017; SOUTO-MARTINEZ *et al.*, 2017; MARTÍNEZ-MUÑOZ *et al.*, 2020; BALASBANEH; RAMLI, 2020).

Among the aspects to be incorporated for the development of environmentally sustainable projects, the optimization of the structural design is extremely important, since the characteristics of the structural system influence mechanical, economic, and environmental performances of the building (FRAILE-GARCIA *et al.*, 2017; XIAO *et al.*, 2018). Nadoushani and Akbarnezhad (2015) indicate that the selection of the best structural design alternative, in environmental aspects, depends on many specific parameters and should only be done after a detailed analysis. Moncaster *et al.* (2018) observed that the choice of a structural system with lower pollutant emissions has clear implications for mitigating climate change and therefore should always be considered. Reinforced concrete stands out as the most widely used structural material worldwide, with high consumption of materials, particularly concrete, steel, and wood (SALGADO; APUL; GUNER, 2020; SCOPE; VOGEL; GUENTHER, 2021).

The sector of Portland cement comprises the largest production chain in civil construction, with an annual average of 20 billion tons of concrete produced worldwide. The consumption of Portland cement in this sector is approximately 3.5 billion tons per year. One should note that the production of Portland cement is extremely impactful since each ton of produced Portland cement uses approximately 1.5 tons of raw materials and between 4000 MJ and 7500 MJ of energy, in addition to the emission of about a ton of CO_2. Thus, Portland cement is recognized as a major source of CO_2, being responsible for about 80% of the total CO_2 emitted in concrete production (DOSSCHE *et al.*, 2016; NOPARAST *et al.*, 2021).

Regarding reinforcement, it is estimated that 30% of all steel produced is consumed by the construction sector, which represents about 400 million tons per year (SCOPE; VOGEL; GUENTHER, 2021). In addition to the high energy demand for its production, it is estimated that each ton of steel produced releases approximately 1.9 tons of CO_2 (SALGADO; APUL; GUNER, 2020).

One way to reduce environmental impacts in reinforced concrete structures lies in the efficient use of materials, from the in-depth study of the structural design, and through the simulation of models that contemplate the variation of concrete strength, reinforcement rate, piece dimension, and consumption of wooden forms (SHARMA *et al.*, 2011). From these simulations, one can observe that there are several structural models for the same building, resulting in different consumption of resources and, consequently, different environmental performances (FRAILE-GARCIA *et al.*, 2016).

In the study by Fraile-Garcia *et al.* (2016), it was observed that the impacts generated by reinforced concrete structures are affected by numerous variables, such as the thickness of structural elements, utilized materials, and structure typology. In the work of Souto-Martinez *et al.* (2017), in which the objective was to quantify and reduce the possible environmental impacts of concrete buildings, the authors found that innovations in structural geometries maximize the potential of reinforced concrete elements to sequestrate CO_2 by approximately 21%. Furthermore, Dossche *et al.* (2016), Ferreiro-Cabello *et al.* (2017), Balasbaneh and Ramli (2020), and Ghayeb, Razak and Sulong (2020) found that cement and steel contribute significantly to environmental impacts, therefore creating the need to optimize the consumption of these materials in structural design.

Thus, knowing the importance of reinforced concrete structures in the construction sector and the high consumption of materials and pollutant emission in production processes, it is extremely relevant to implement structural design optimization tools, focusing on the assessment of environmental performance, such as Life Cycle Assessment (LCA). LCA is a tool used to identify the potential environmental impacts of a product, service, or process throughout its life cycle. In addition, the tool is often used to analyze conditions and, consequently, search for environmentally viable alternatives (FRAILE-GARCIA *et al.*, 2016; POMMIER *et al.*, 2016; HOLLBERG *et al.*, 2021).

Therefore, LCA is indicated to assess the potential environmental impacts of buildings, such as resource consumption, pollutant emission, and waste generation, as it is a broad methodology, applicable in all phases, internationally standardized, and widely used (CHO *et al.*, 2012). LCA can be a methodology used in project decision-making, supporting the choices of the structural system to be used in buildings, following the guidelines for sustainable development, aiming at respecting and preserving the environment (DIVANDARI; NAJARI, 2016; MONCASTER *et al.*, 2018; MARTÍNEZ-MUÑOZ; MARTÍ; YEPES, 2020; HOLLBERG *et al.*, 2021).

In this context, the objective of this work was to analyze the use of the Life Cycle Assessment (LCA) methodology to assist in decision-making in structural projects of reinforced concrete, aiming at improving environmental performance by using different classes of concrete strength, altering dimensions of structural elements, as well as changing the consumption of the structure materials (concrete, steel, and wooden form). Were studied structural models for an eight-story building, with six classes of concrete compressive strength (fck), ranging from 25 to 50 MPa [23], for comparative analysis. The LCA methodology and, also, an economic study was employed as tools to aid in the decision-making process.

Research method

The objective of this study was to estimate the potential environmental impact of a building, in all its phases, from cradle to grave, i.e., extraction of raw material, manufacture of raw material, transport to the construction site, production of the building, use phase, transport to the final destination, and final disposal. To achieve this goal, the Life Cycle Assessment (LCA) method was used. The structure of the LCA method is constructed based on the ISO 14040 (INTERNATIONAL…, 2006) standard. The four phases of an LCA study required by the ISO 14040 series are objective and scope definition, life cycle inventory analysis, life cycle impact assessment, and data interpretation. The objective and scope definition phase aims at defining the goals for LCA application. In the inventory analysis phase, mass and energy flow entering and leaving different stages are listed and, in the impact assessment phase, one calculates the environmental load of the target installation. In the end, at the interpretation stage, one identifies the significant issues of the study and defines conclusions and recommendations.

In this analysis, the attempt to determine the function by columns, beams and slabs alone was not considered convenient. The structure of a building works holistically, with the interaction between all components with their interconnected functions. A structural part can perform several functions in the structure, depending on external and internal requests, depending also on the interaction between them. Therefore for the Life Cycle Assessment, the complete structure of the building, the complete structural network, was adopted as the functional unit. Instead of analyzing the isolated sections (which in all strength classes must comply with the executive regulations), the study considers the rates of concrete and steel per m² for this evaluation.

Description of the case study

The LCA was performed with the functional unit of a standard eight-story Brazilian residential building (Figure 1), according to NBR 12721 (ABNT, 2006). It is worth mentioning that this building typology is widely executed in Brazil, acting as a case study for this work.

The typical Brazilian residential building with eight floors is composed of a ground floor and seven standard floors. On the ground floor there is an entrance hall, elevator, stairs and four apartments with two bedrooms, living room, bathroom, kitchen and tank area. Outside, there is a waste room and thirty-two uncovered parking spaces. In the typical floors there is a circulation hall, stairs and four apartments per floor with two bedrooms, living room, bathroom, kitchen and laundry area. The total real area of the typical Brazilian residential building with eight floors is 2,078.00 m².

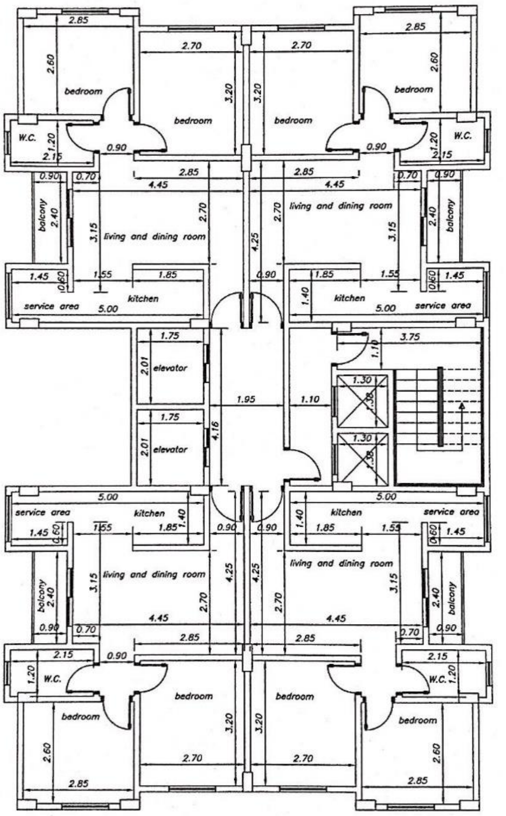
Application of LCA in the case study

Objective and scope definition

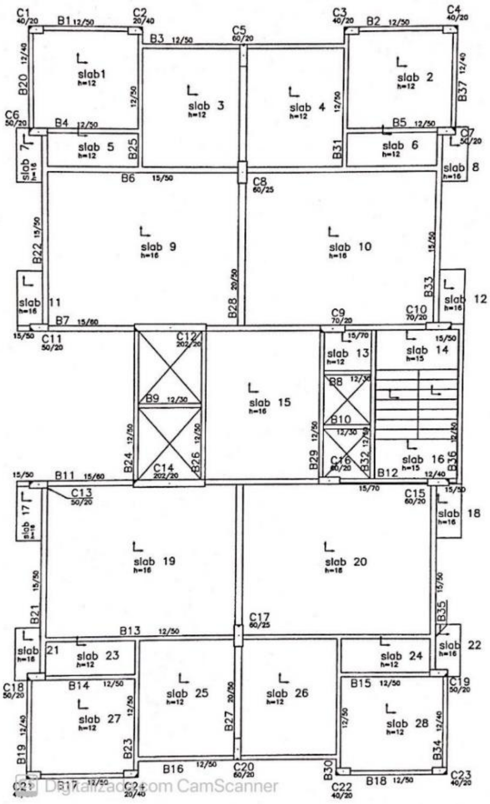
This study applied LCA in a building with a reinforced concrete structure, designed with different values of characteristic resistance to compression, for comparative analysis, to account for the environmental impacts of each of the alternatives, which directly reflect on materials consumption and in the size of structural parts that make up the structure.

The functional unit is defined by ISO 14040 (INTERNATIONAL…, 2006), as a quantified performance of a product system for use as a reference unit. In this assessment, as mentioned above, the functional unit adopted was a standard eight-story Brazilian residential building, with 2.078 m² structural area and the with the ability to withstand the characteristic load of 5,5 kN/m² (without counting the weight of the structure itself). For this functional unit, a comparative LCA was performed, analyzing the structural design with six different concrete classes.

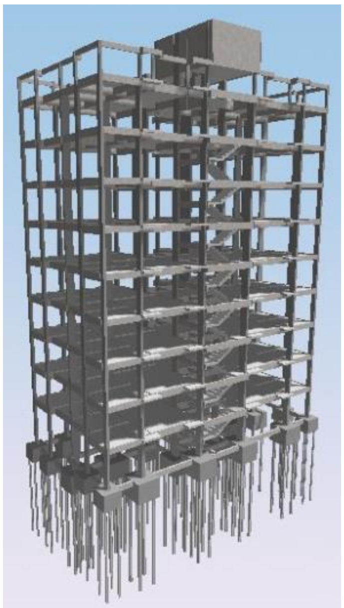
Figure 1 – **Design of the typical Brazilian residential building**



(a) Floor plan



(b) Structural design



(c) 3D design

The structural system in reinforced concrete has the function of supporting the building, which is, absorbing and transmitting to the foundations all acting forces, with pre-defined safety, according to the minimum requirements of NBR 6118 (ABNT, 2014) and the prescriptions of NBR 6120 (ABNT, 2019). The description of the function of the structural system is shown in Table 1.

The minimum expected durability of reinforced concrete structure project is 50 years for structural systems such as the one studied in this article, as estimated by NBR 15575 (ABNT, 2013) in reference to NBR 8681 (ABNT, 1984). Although the concrete classes are different, is important to the transparency of this evaluation to clarify that for this study all functional units adopted were considered with similar service life.

The results obtained through the structural design of the building are valid and safe, as they resulted from the envelope of calculation requests, formed by a minimum of fifty combinations between Ultimate Limit State (ruin) and Service Limit State, which were then considered all normative requests (such as winds, accidental, permanent loads). It should be noted that the analysis of the superstructure was carried out without considering the foundations, which can vary in different locations.

Since the functional unit considered was the building, complete structural lattice, with 2,078.00 m², its structural design was carried out with six classes of concrete characteristic resistance to compression (fck), which are: C25 (25 MPa), C30 (30 MPa), C35 (35 MPa), C40 (40 MPa), C45 (45 MPa), and C50 (50 MPa). Was used the *TQS* Structural Engineering Software (version 18.17) to execute the structural project. During the process of designing the structure, was started the project using the resistance class C25. Then, there was a change in the strength class of the concrete, without changing the dimensions of the structural components, to class C30. The maintenance of dimensions in the analysis of structural parts between the values of classes C25 and C30 aimed at verifying the behavior and trends of the results obtained. The definition of the dimensions immediately results in different reinforcement rates per volume of concrete in the structure, significantly altering the consumption of materials. For concrete classes between C35 and C50, a progressive reduction was made in the dimensions of slabs, beams, and columns, until reaching the smallest possible dimensions that still met the required demands of safety and service (ABNT, 2015, 2019, 1984). When attempting to reduce the dimensions of structural parts from class C45 to class C50, it was verified that the operation was impeded due to normative prescriptions. As a result, dimensions of the concrete class C45 were maintained. It is worth mentioning that different reinforcement rates were calculated for each class of concrete studied. Quantities are shown in Table 2. As for geographic scope, the building is located in the southeast region of Brazil, in a city in the south of Minas Gerais state, with approximately 150,000 inhabitants (Poços de Caldas-MG).

Table 1 – **Function of the structural system, according to ABNT 6118 and ABNT 6120**

<table>
<tr><th>Environmental Aggressiveness Class</th><th colspan="3">Moderate II - Urban Region</th></tr>
<tr><td rowspan="2">Reinforcement cover</td><td>Beams</td><td colspan="2">3 cm</td></tr>
<tr><td>Slabs</td><td colspan="2">2.5 cm</td></tr>
<tr><td rowspan="4">Requests Adopted</td><td rowspan="3">Slabs</td><td>Permanent overload</td><td>1 kN/m²</td></tr>
<tr><td>Accidental Overload</td><td>1.5 kN/m²</td></tr>
<tr><td>Walls on slabs</td><td>5 kN/m</td></tr>
<tr><td>Beams</td><td>Walls</td><td>5 kN/m</td></tr>
<tr><td rowspan="5">Wind</td><td>Basic Speed (S1)</td><td colspan="2">35 m/s</td></tr>
<tr><td>Topographic Factor (S2)</td><td colspan="2">1</td></tr>
<tr><td>Roughness Category (S2)</td><td colspan="2">IV</td></tr>
<tr><td>Building Class (S2)</td><td colspan="2">B</td></tr>
<tr><td>Statistical Factor (S3)</td><td colspan="2">1</td></tr>
</table>

Table 2 – **Quantification of materials for the production of concrete - values considered for each m³ of concrete**

Materials	Concrete Class					
	C25	**C30**	**C35**	**C40**	**C45**	**C50**
Portland cement CP III (kg)	310	340	370	389	405	421
Sand (kg)	870	770	744	739	734	730
Gravel (kg)	930	970	960	1,031	1,035	1,038
Water (liter)	180	185	190	177	173	169

The boundaries of the system are divided into four elementary processes:

(a) reinforced concrete structure;

(b) concrete distribution on site;

(c) use phase; and

(d) final landfill.

Figure 2 illustrates the product system flowchart.

The descriptions of characteristics concerning impact categories and the comments on the results obtained follow the EDIP 1997 method. This method is also indicated for its global application scope, since there are no methods developed for Brazil or South America (FERRO *et al.*, 2018; SOUZA *et al.*, 2018).

The study is mostly based on secondary data, obtained from the software *GaBi* and the database *Ecoinvent*, concerning chains of electricity production, water extraction and processing, cement production, steel production, wood production, final deposition of civil construction, and input transportation by truck (diesel).

Some primary data has been collected, replacing secondary ones. The primary data collected relate to the quantity of raw material for cement production, directly informed by the manufacturer, and the concrete production phase at the plant, including its transportation to the construction site. Was used data on the production process of crushed stone, taken from the study by Rossi (2013).

Life Cycle Inventory (LCI)

From the collected data and by using the studied functional unit, the Life Cycle Inventory (LCI) was carried out. As this is a comparative study, it is worth mentioning that six classes of compressive strengths of concrete were analyzed. Results of the material consumption of the functional unit, for the execution of the structure, as well as its indexes, are presented in Table 3. For this analysis, was considered the reservoir cover and bottom, the roof, the 2nd to 8th-floor types, the 1st floor, the ground floor 1, and the ground floor 2.

In Table 3 it is observed that class C40 has the lowest cement consumption index/m², 66.13 kg/m², despite not having the lowest concrete consumption index/m², 17 m³/m², higher than class C45 and C50, both with 16.8 m³/m².

Classes C45 and C50, despite having a greater reduction in concrete volumes compared to class C40, had a higher consumption of cement/m², but still lower than the reference class C25 and C30 (which did not suffer a reduction in structural parts in compared to C25). Such information is important in further analysis of some potential impact categories.

In the case of steel consumption, through the transposition of the indices referring to the consumption of steel/m3 of concrete and steel/m² structural area, the graph shown in Figure 3 is presented.

Figure 2 – **Product system flowchart**

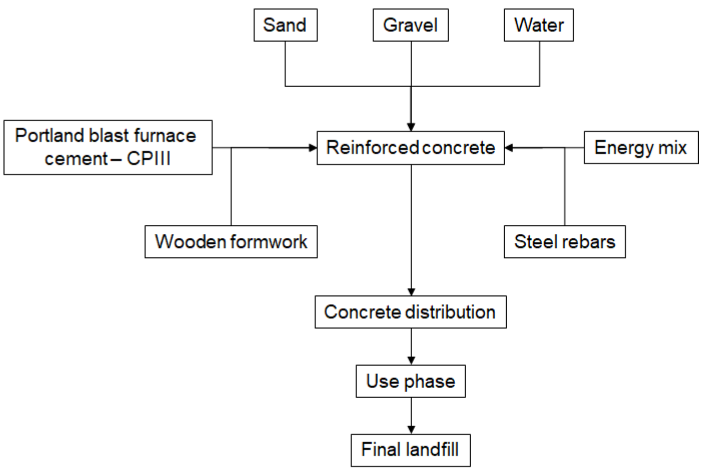
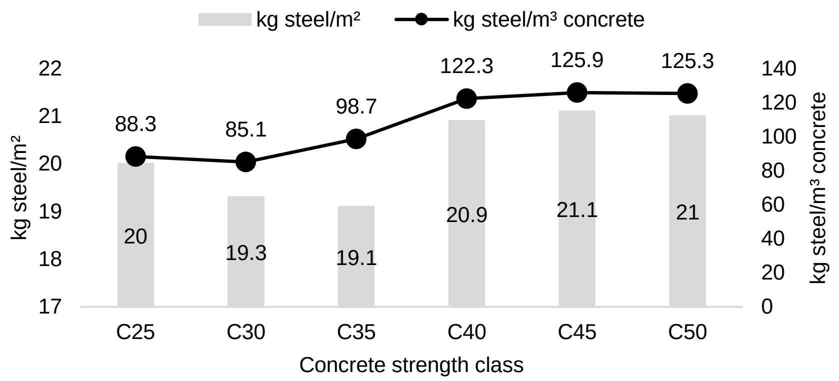


Table 3 – **Consumption of materials and indexes of concrete classes C25 - C50**

Concrete Class	Concrete		Wooden Forms		Steel		
	Consuption (m^3)	Rate (m^3/m^2)	Consuption (m^2)	Rate (m^2/m^2)	Consuption (kg)	Rate (kg/m^2)	Rate (kg/m^3)
C25	471.4	0.23	4,596.8	2.2	41,619.2	20.0	88.3
C30	471.4	0.23	4,596.8	2.2	40,130.8	19.3	85.1
C35	401.0	0.19	4,464.6	2.1	39,596.1	19.1	98.7
C40	355.6	0.17	4,266.6	2.05	43,506.8	20.9	122.3
C45	348.9	0.168	4,266.6	2.05	43,938.3	21.1	125.9
C50	348.9	0.168	4,266.6	2.05	43,704.7	21.0	125.3

Figure 3 – **Consumption steel/m² and steel/m³ concrete x concrete strength class**



In Figure 4 its can be seen that class C35 has the lowest consumption index of steel/m², 19.1 kg/m², despite not having the lowest consumption index of steel/m³ of concrete, 98.7 kg/m³. With the reduction of the section due to the increase in the strength class of the concrete, there was a reduction in the structural mass of steel/m². In the case of steel, the section reduction for this reference strength class.

Life Cycle Impact Assessment (LCIA)

From the conduction of the LCI, the Life Cycle Impact Assessment (LCIA) was implemented, defining the classification of impacts and later their characterization. The characterization factor employed was the EDIP 1997 method. The impact categories analyzed were acidification potential, global warming potential, eutrophication, ozone depletion potential, photochemical ozone formation (high and low NOx), with main characteristics observed in studies of concrete structures (YAVARI *et al.*, 2017; MEEX *et al.*, 2018; BALASBANEH; RAMLI, 2020; HOLLBERG *et al.*, 2021).

Characterization of the impact categories was performed using the software *GaBi* (PE International GmbH). The *GaBi* software and the Ecoinvent database are in line with recommendations of the documentation in the International Reference Life Cycle Data System (ILCD). The *GaBi* documentation also includes criteria of the ILCD format, created by JRC-IES of the European Commission, European Platform on LCA, Copyright©, European Commission.

Life Cycle Interpretation

In this stage, the results obtained were interpreted, generating subsidies for decision-making and highlighting opportunities to improve the environmental performance of buildings.

Results and discussions

General results of potential environmental impacts for the six structural models are shown below in Table 4 and Figure 4. Analyzing the results presented, one can identify that the structural models that had the higher impact potential are the resistance classes C25 and C30, while classes with the least potential impact were C40, C45, and C50.

Table 4 presents the absolute values of environmental impacts for each category analyzed. One observes that there were slight differences between the models analyzed for some impact categories, such as OD (ozone depletion), and significant differences for other categories, that are indicated in the table and explained in the following paragraphs.

Solvents, aerosols, foams for insulation, sand (reflection of ultraviolet radiation), emissions in the production of steel, and others are among the chemical substances used in civil construction that affect the Ozone Depletion category. However, it is worth noting that most substances that emit CFC gases are already massively prohibited, which may explain the low magnitude of the impact found in this study. Hence, this research will not delve into the discussion of this category.

The C30 concrete class had the highest impact potential for 67% of the studied categories (AC, GW, ET, and HPO). These results can be explained by the increased strength of concrete in this class, concerning C25, though without reduction in the dimensions of beams and columns, as occurred progressively in the classes between C35 and C50. Although showing the same consumption of concrete as class C25, class C30 stood out due to higher cement consumption per area, with 78.2 kg/m² of cement being used, which may explain the consequent increase in the potential for impact of this resistance class compared to the reference (class C25, with consumption of 71.3 kg/m²), despite the reduction in steel consumption obtained (20.0 and 19.3 kg/m² for classes C25 and C30, respectively).

Concrete consumption occurred in the range of 0.168 m³/m² and 0.17 m³/m² among structural models for the three classes with the lowest overall potential impacts (C40, C45, and C50). Steel consumption rates for these three strength classes ranged from 122.3 kg/m³ to 125.3 kg/m³ of concrete, corresponding to values from 20.9 kg/m² to 21.1 kg/m². As for the consumption rates of wooden forms, these three classes of resistance showed equal results up to the second decimal place, 2.05 m²/m² of wooden form/built area, due to regulatory limitations.

Figure 4 graphically highlights the dimension of the potential environmental impacts for each resistance class analyzed in this study. From the Figure 4, can observed that the variation in the environmental performance between the classes, demonstrated by the aforementioned impact categories, in addition to the resistance class with the least potential impact for this analysis, the C40 class.

Among classes C40, C45, and C50, concrete class C40 had the lowest potential environmental impacts for 67% of the impact categories analyzed, namely acidification (AC), global warming (GW), photochemical ozone formation - high NOx (HPO), and photochemical ozone formation - lower NOx (LPO). The lower impacts of the structural solution class C40 ranged from 7.4 to 21.2% for four of the six categories analyzed.

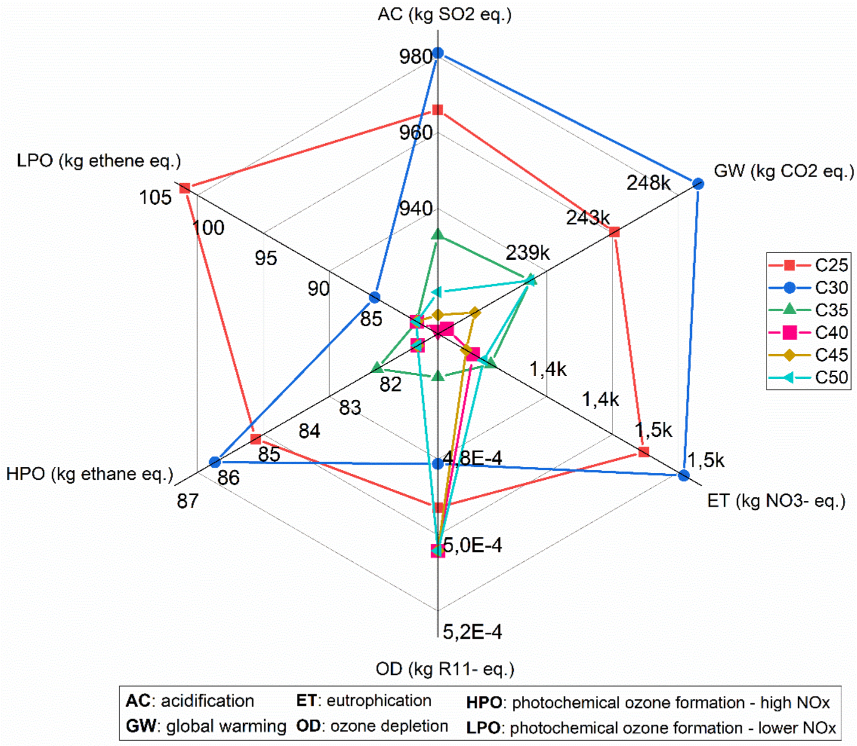
These results can be explained due to the reduction of structural elements with the increase of resistance classes (C25 to C45) and the consequent reduction in the amount of concrete and steel consumed. This result is supported by the values of lower cement consumption (66.13 kg/m²) and by presenting the lowest consumption rates for steel (122.3 kg/m³) and concrete (20.9 kg/m²).

Table 4 – **Potential environmental impacts of the structure of a standard building with eight floors [25] and 2,078 m²**

Impact Category	Unit	C25	C30	C35	C40	C45	C50
AC	kg SO2 eq.	966	981	933	908	912	918
GW	kg CO2 eq.	243,126	249,360	236,892	230,658	232,736	236,892
ET	kg NO3- eq.	1,477	1,500	1,390	1,380	1,376	1,386
OD	kg R11- eq.	0.00049	0.00048	0.00046	0.00050	0.00050	0.00050
HPO	kg Ethane eq.	85	86	82	81	81	81
LPO	Kg Ethene eq.	104	86	82	82	82	82

Note: AC: acidification;
GW: global warming;
ET: eutrophication;
OD: ozone depletion;
HPO: photochemical ozone formation (high NOx); and
LPO: photochemical ozone formation (lower NOx).

Figure 4 - **Distribution of potential environmental impacts for different classes of concrete strength**



For the GW category, the C40 class had the lowest environmental impact, while the C30 class had the highest impact potential. The percentage reduction was 7.5%, and although it seems to be a low value, converting to the value of kg of CO_2 equivalent, the possible choice of class C40 for the production of this particular standard building with eight floors, instead of choosing class C30, would save approximately 18 thousand kg of CO_2 equivalent emitted to the planet.

By separately investigating the contribution of each of the three main components of the reinforced concrete structure (concrete, steel, and wooden forms) to the impact categories analyzed, the reference class C25 (minimum strength class for reinforced concrete structures in Brazil) was chosen for a detailed evaluation. The detailed results are shown in Table 5 and Figure 5.

In general, for class C25, the wooden forms used in the construction of the building are responsible for most of the potential environmental impacts, presenting potential impacts of up to 61.7%, represented by impact categories: AC, ET, HPO, and LPO. This result is explained by the great distances involved in wood transportation from the extraction site to the consumption centers, which causes the high amount of emissions shown in Table 6.

The native sawn wood from the Amazon rainforest, accompanied by a Document of Forest Origin (DOF) from the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA), from the Ministry of the Environment, is transported in Brazil over long distances by road. A large part of the volume of sawn wood, originating in the Amazon, travels between 1,500 and 3,000 km. In this research, a distance of 1,956 km was assumed, from the place of extraction to the place of consumption. In this context, the emission factor ranges being between 12.8 g of CO_2/t.km and 50.6 g of CO_2/ t.km, depending on the type of cargo truck (CAMPOS; PUNHAGUI; JOHN, 2011).

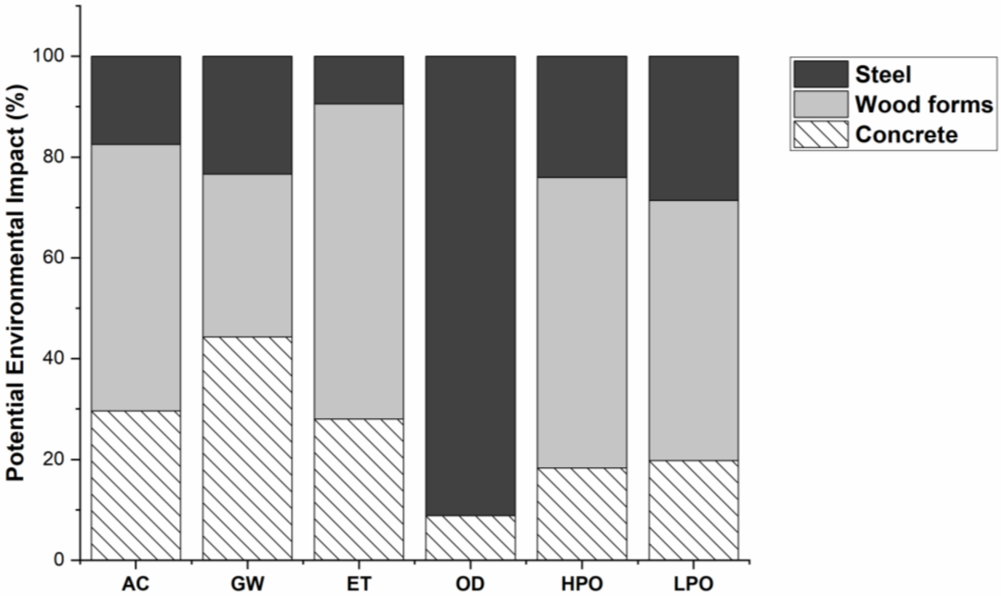
Some works propose the replacement of sawn wood by plywood (AHMAD *et al.*, 2013; PUETTMANN; CONSULTANTAS; ONEIL, 2013; POMMIER *et al.*, 2016; JIA *et al.*, 2019). Jia *et al.* (2019) show that plywood is a product commonly used in civil construction to replace traditional materials. Pommier *et al.* (2016) mentioned that plywood panels have been marketed worldwide for over 100 years, with successive innovations, from the use of environmental-friendly glues to the employment of different types of wood treatment, thus more environmentally appropriate.

Table 5 – **Potential environmental impacts of a standard building with eight floors [25], concrete resistance class C25, and 2,078 m²**

Impact category	Unit	C25 (global value)	Concrete	Wooden forms	Steel
AC	kg SO_2 eq.	966	283	505	167
GW	kg CO_2 eq.	243,126	105,874	77,094	55,898
ET	kg NO_3- eq.	1,477	0,408	0,912	0,137
OD	kg R11- eq.	0,00048833	0,00004209	0,00000004	0,00043430
HPO	kg ethane eq.	85	16	49	20
LPO	kg Ethene eq.	104	17	44	24

Note: AC: acidification;
GW: global warming;
ET: eutrophication;
OD: ozone depletion;
HPO: photochemical ozone formation (high NOx); and
LPO: photochemical ozone formation (lower NOx).

Figure 5 – **Contribution of potential environmental impacts of class C25 for the different impact categories analyzed**



The production of plywood in Brazil has been increasing, with an annual production of about 260,000 m³. Compared to sawn wood production centers, plywood production centers are located closer to consumer centers in Brazil. Compared to long-distance transportation, closer locations contribute substantially to the control of environmental impacts (AHMAD *et al.*, 2013; POMMIER *et al.*, 2016; JIA *et al.*, 2019).

The distances considered for wood transportation in this study caused an increase in the potential impact generated by the wooden forms of approximately 77,000 kg of carbon dioxide (CO_2) and 500 kg of sulfur dioxide (SO_2) emitted for the construction of a standard eight-story building. The use of plywood panels, which have shorter transportation distances between factories and consumer centers, can help to mitigate these impacts.

The C25 class presented steel as the material with the higher impact on OD, with the contribution of 88.9%. This result is related to emissions of halocarbons, that is, CFC, HCFC, halogens, and other gases containing bromine and chlorine, during the steel production process. According to Renzulli *et al.* (2016), the impact caused by the manufacture of steel in the ozone layer is mainly due to emissions from the blast furnace and, depending on the geographic scope, emissions from the transportation of raw materials used.

Among structure components, concrete was responsible for the higher environmental impacts in the GW category, mainly related to emissions during cement production, that was responsible for 43.5% of the potential environmental impacts. Xiao *et al.* (2018) studied the environmental impacts of two 12-story twin towers, one with natural aggregate and the other with recycled aggregate. The authors mention that the production of cement, together with long-distance transportation of raw materials, was the main responsible for the impact on global warming of the studied buildings. Dossche *et al.* (2016) still add that the production of Portland cement is largely responsible for the impacts of concrete production, with around 74% to 81% of the total CO_2 emitted in the production of concrete only.

According to Scrivener, John and Gartner (2018), cement is the largest mass-manufactured product on Earth and constitutes an important part of the built environment, though its environmental impact has been supporting research on mitigating CO_2 emissions. The reduction in concrete consumption, by the reduction in dimensions structures in the classes studied, can mitigate the potential environmental impact, as can be noticed by the lowest GW value of the C40 class.

Economic implantation analysis

The results of this study demonstrated that class C40 had the lowest results of potential environmental impacts in approximately 67% of the impact categories. Complementarily to the LCA study, a total cost survey was carried out for the implantation of the structures to the different classes of concrete strength, as seen in Table 6. It is important to note that the survey was based on average values practiced in the region of the study.

From Table 6, one can see that resistance classes with the lowest cost were C35 and C40, while the classes with the highest cost were C25 and C50. The C50 class, which presented the highest cost among resistance classes (U$ 53.87/m²), showed values 7.9% and 6.1% higher than the C35 and C40 classes, respectively. While class C25, used as a reference, showed higher values than classes C35 and C40, which had lower cost/area indexes, around 6.6% and 4.7%, respectively.

Among structure components, steel was responsible for an average of 44% of the cost, concrete accounted for a mean value of 35%, and wooden forms were responsible for an average of 21% of the total cost of the structure. Class C30 presented a higher percentage of cost/area relative to concrete, among other classes, with a value of 37.3%. This high percentage can be explained due to the increase in the strength class and respective cement content, without reducing the dimensions of the structural elements.

Figure 6 correlates two of the most used impact categories to highlight environmental impacts, global warming and acidification, and the cost per square meter for each class of concrete strength. Despite the variation of these values geographically and temporally, the resistance classes with the lowest cost in this study were C35 and C40.

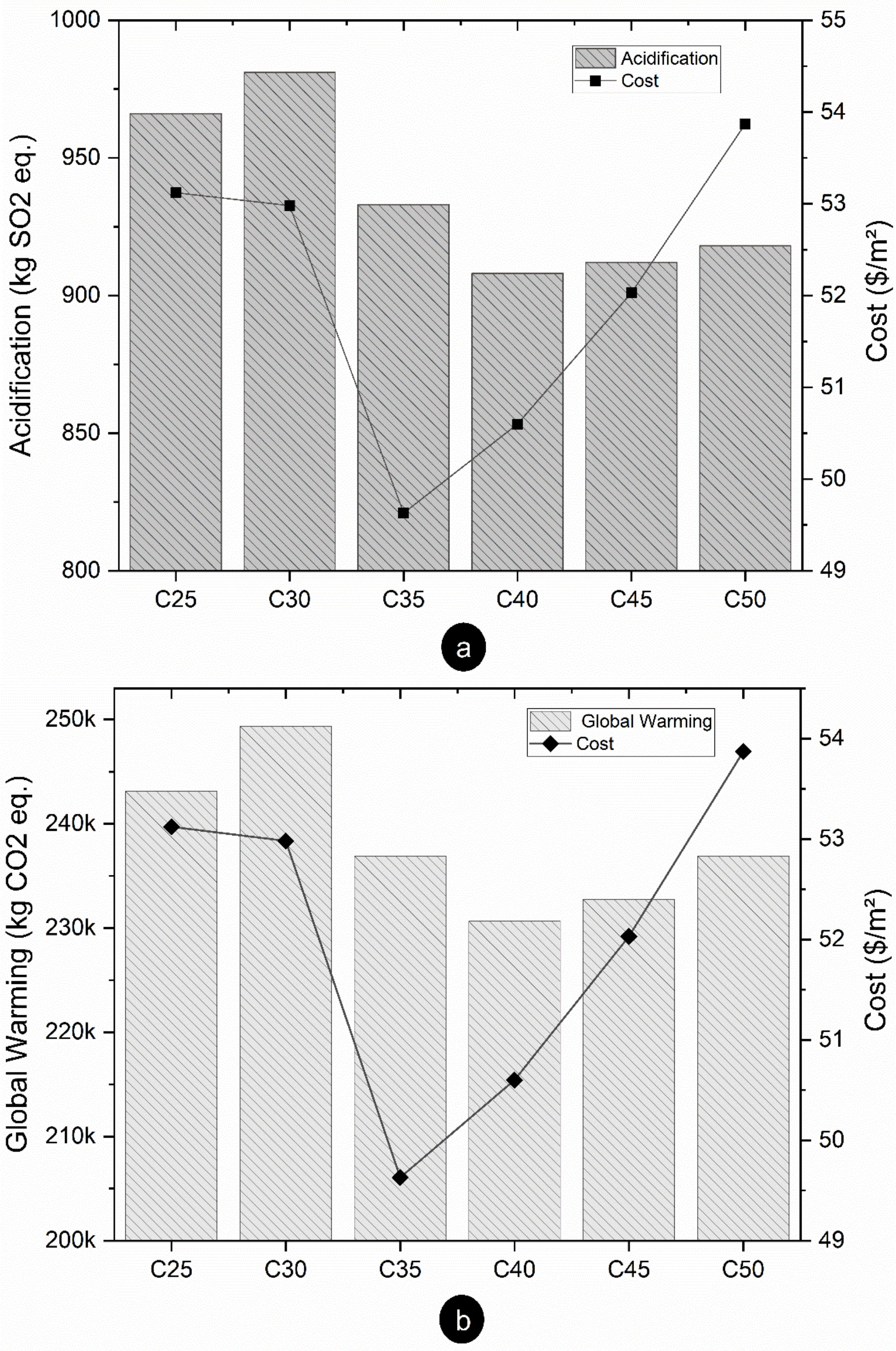
To the detriment of the correlation of environmental impacts and associated costs, class C40 was the second lowest cost among studied classes (only 2% above the cost of C35) and presented the lowest impact value on global warming, as can be seen in Figure 4. In this case, it should also be noted that the choice of C40, instead of C35, has a benefit related to structure durability, since an increase in concrete strength is directly related to the durability of the reinforced concrete structure. Thus, among the classes presented and the impact categories analyzed, the convergence of technical, environmental, and economic indicators presented in this study indicate class C40 as the most sustainable choice for the execution of the structure of the standard eight-story building addressed.

Table 6 – **Structure costs/m² of the different concrete strength classes[1]**

Resistance Class / Material and Cost	C25	C30	C35	C40	C45	C50
Concrete (m³/m²)	0.23	0.23	0.19	0.17	0.168	0.168
Cost (U$/m²)	19.11	19.77	17.16	16.33	17.56	19.84
Steel (kg/m²)	20	19.3	19.1	20.9	21.1	21
Cost (U$/m²)	22.64	21.83	21.60	23.67	23.87	23.78
Wooden Forms (m²/m³)	2.2	2.2	2.1	2.05	2.05	2.05
Cost (U$/m²)	11.38	11.38	10.86	10.60	10.60	10.60
Total (U$/m²)	53.12	52.98	49.63	50.60	52.03	53.87

Note: [1]Unit costs based on the table of the National System of Costs Survey and Indexes of Construction (SINAP) of March 2021: steel U$ 1.13/kg; wooden form U$ 5.17/m²; concrete (pumping included): C25 U$ 83.09/m³; C30 U$ 85.96/m³; C35 U$ 90.26/m³; C40 U$ 95.99/m³; C45 U$ 104.58/m³; C50 U$ 116.04/m³.

Figure 6 - **(a) Analysis of the impact of Acidification for concrete strength classes versus cost ($/m²); and (b) Analysis of the impact of Global Warming for concrete strength classes versus cost ($/m²)**



Conclusions

The initial objective of this study was achieved, demonstrating that the use of the LCA methodology can assist in decision making during the design process of reinforced concrete structures, identifying critical points subject to adjustments, and aiming at the best environmental performance of the structural design.

Results showed that the structural models for classes C40, C45, and C50 presented the best results for the impact categories evaluated. Particularly, the C40 class presented as the best option for the evaluated functional unit (the typical Brazilian 8-story building), with the lowest potential impact for 67% of the categories studied, including the possibility of saving 18 thousand kg of CO_2 emitted to the planet, if this class is chosen instead of class C30.

Analyzing the contribution for the potential impact, the wooden forms was the major contributor for four of six impact categories, mainly regards to the wood transportation. Other materials and solutions for wooden forms should be studied, such as the use of plywood panels, shorter transport distances (which varies regionally and from country to country), or even the possibility of using precast slabs, which practically do not require shoring, and can be the basis for future studies.

With this assessment, suggestions can be made to the structural designers for decision-making in the design of buildings similar to the functional unit analyzed, aiming at the maximum reduction of structural parts and the verification of concrete and steel consumption rates.

In the present study, it was also evident that the environmental assessment carried out in conjunction with the economic analysis enables to obtain an optimal result for resource use (concrete, steel, and wooden forms) in structures. Additionally, the reduction of the dimensions of structural elements together with the elevation of concrete strength were fundamental for the optimization of the project and, consequently, to reduce costs and potential environmental impacts of the reinforced concrete structure.

Regarding the economic analysis of the structure, the lowest values obtained were for structural models C35 and C40. In this context, the C40 model presents itself as the optimal option in this study, in addition to presenting an increase in concrete durability compared to C35, since the increase of the concrete class is directly proportional to the longevity of the structure.

The designer is largely responsible for the overall efficiency of the structural design, decisively influencing the performance, durability and final cost of construction. The realization of the LCA for the 5 strength classes of the evaluated functional unit showed that the reduction of structural parts, provided by the increase in the strength classes of concrete, is a favorable procedure for the better environmental performance of the structure. The recommendation to structural designers, for decision making in the design of buildings similar to the analyzed functional unit (8 floors), is to use as the first goal the maximum reduction of structural parts. Then the use of class C40 as the initial objective and the verification of the rates of concrete and steel by the structural area, in the case of this class of values on the order of 0.17 m³/m² and 20.9 kg/m² (corresponding to 122.3 kg /m³ of concrete), respectively. Consumption rate values are easily obtained using of calculation and verification programs routinely in structural design offices and often requested by contractors.

Finally, some future research can be recommended after this study, such as to test different materials and constructive units, like slabs, can be evaluated for the structure design. Variations can be tested in sensitivity analyzes or in adoption of consequential LCA to expand the results obtained. This assessment focused on the economic study of the implantation of the structure, however new research should be encouraged to study the cost of maintaining the building.

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