Cleaner Engineering and Technology 5 (2021) 100256

Contents lists available at ScienceDirect

Cleaner Engineering and Technology

journal homepage: www.sciencedirect.com/journal/cleaner-engineering-and-technology

Life cycle costs and impacts of massive slabs with varying concrete cover

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ARTICLE INFO

Keywords:
Concrete cover
Reinforced concrete structure
Life cycle assessment (LCA)
Life cycle costs (LCC)

ABSTRACT

Considering construction costs, predicted service life, and related environmental impacts, this paper evaluates the influence of varied concrete cover thicknesses in the life cycle of a reinforced concrete structure. Environmental impacts and costs of a structural element (slab) are evaluated using Life Cycle Assessment (LCA) and Life Cycle Costs (LCC) varying the concrete cover thickness. Larger covers increase material consumption (16.27% of steel reinforcement), initial costs (up to 2.44%), and environmental impacts (from 6.46% to 12.51%). However, the enlarged structure service life (durability) provides lower yearly costs (reduction of 74.39%) and environmental impacts (up to 73.15% for ODP). The results highlight that an increase in concrete cover thickness enhances the structure's durability, reduces costs and environmental impacts per year of predicted service life, contributing to reach more sustainable structures.

1. Introduction

Concrete cover is a protective mechanism in reinforced concrete structures that maintains the high alkalinity and the passive film over the reinforcement. If the passive film breaks down (depassivation), corrosion can initiate, which occurs when the cover degrades (chemically, physically, or mechanically), chlorides penetrate to the reinforcement or cover concrete carbonate (American Concrete Institute, 2016).

The durability of reinforced concrete structures is highly dependent on the characteristics of this cover (Associação Brasileira de Normas Técnicas, 2014), mainly its concrete quality and thickness (Alexander et al., 2008). These parameters are essential to quantify the structure's design service life (American Concrete Institute, 2002), or a quantitative term of durability (International Organization for Standard, 2014). The design service life is when the building (or a part of it) performs the function proposed and constructed for by considering the standard requirements at the time of construction (Kelly, 2007), or a measure over time of the building's durability (Associação Brasileira de Normas Técnicas, 2013). Most investigations study structural elements due to their difficulty replacement, significant repair costs, complexities associated with executing the repair work, and associated risks.

Standards from different regions (e.g., Brazil ABNT NBR 6118, Spain EHE 08, UK BS 8500–1, Australia AS 3600, New Zealand NZS 3101–1, EUA ACI 318; Europe EN, 1992-1-1) specify levels of concrete cover quality (e.g., minimum concrete strength, maximum water/cement ratio, minimum binder content, supplementary cementitious materials) and cover thickness (e.g., minimum, nominal, execution tolerance), and associating them with classes of environmental aggressiveness (exposure classification) to aim at an appropriate structural performance. While these are guidelines for the specification of appropriate cover are in place, this is a choice made by structure designers that are often neglected (Menna Barreto et al., 2018). Concrete cover issues are frequent in reinforced concrete construction and originate in the design phase (Menna Barreto et al., 2018), when designers incorrectly specify the cover thickness. The issue persists in the construction phase, where the constructed cover surpasses the standard's tolerances and contributing to a widespread problem.

Clark et al. (1997) investigate the specified cover into 25 construction sites and found that it was not achieved at a significant number of locations. Neville (1999) believes that there is an endemic problem of improper cover. Ronné (2005) stated that despite a common perception that cover is a relatively simple subject, the terminology for cover suggests the converse. Maran et al. (2015) and Menna Barreto et al. (2018) measured the concrete cover in some buildings and concluded that the design cover thickness is not obtained and there is great variability in it.

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https://doi.org/10.1016/j.clet.2021.100256
Received 27 January 2021; Received in revised form 30 July 2021; Accepted 19 August 2021

Insufficient covers accelerate corrosion potential (decrease durability), contribute to possible bond failure (impair reinforcement adherence), and reduce fire resistance (American Concrete Institute, 2002). To avoid these situations, it is necessary to increase the concrete cover thickness, which results in an increase in material consumption. In order to maintain the same cross-sectional area of the concrete element, a larger steel quantity is required; conversely, if the steel quantity is to remain fixed, the concrete cross-sectional area will increase.

Higher material consumption will increase costs and environmental impacts imposed by the construction of the structure. However, these detrimental effects can be offset by the gain in durability that an increased concrete cover can provide, resulting in a sustainable benefit.

Building durability differs from common consumer goods, and their impacts are not only limited to building construction (Morales et al., 2019). A building life cycle considers the extraction and production of the raw materials, transportation to the construction site, building production, operation (e.g., energy consumption, water consumption), maintenance, and final disposal (Comité Européen de Normalisation, 2012). For an accurate impact evaluation of civil construction, a technique is required that encompasses all stages of its life cycle and its interactions. To evaluate and improve building performance, LCA has been widely accepted and is at the center of current standards for assessing building sustainability (Röck et al., 2018).

Reinforced concrete structures are responsible for most of the impacts generated in the building production stage (Ferreiro-Cabello et al., 2016), namely steel and concrete as the most relevant materials for such impacts (Rohden and Garcez, 2018). Concrete is a relatively unsustainable material in a building's structure due to the need for reinforcing steel and the quantities necessary to execute it (Martínez-Rocamora et al., 2016).

Considering the materials consumption costs, durability, and the environmental impacts, a more in-depth study is necessary to evaluate the influence of the concrete cover thicknesses over the structure's life cycle. Studies that evaluate the environmental impacts of reinforced concrete slabs are relatively scarce (Paik and Na, 2019). Besides that, there are very few studies investigating the concrete cover thickness as a principal subject, and none thus far evaluate its effect on the structure's life cycle.

In this way, this study aims to evaluate the economic and environmental life cycle impacts of a massive reinforced concrete slab by varying the concrete cover thickness based on data and theoretical service life models, and by encompassing the majority of nominal concrete covers suggested by international standards. This assessment and quantification of the results of varied cover thickness provides more data to assist in decision-making through a comparison process in reinforced concrete structure projects that can involve designers, executors, clients and users globally.

2. Materials and methods

The functional equivalent, used as an object for comparison, is a reinforced concrete slab, with 4 m × 4 m dimension (theoretical span or calculation span - the distance between the centers of supports) that is simply supported and with 12 cm thickness. It is sized for residential buildings and for local rain protection with nominal covers (minimum cover more execution tolerance) ranging from 15 to 30 mm (measured at each 5 mm). A 30 MPa commercial concrete is assumed from a local concrete producer, reinforced with CA60 steel (in bars) and using molded-in wood formworks.

The reasons for these choices are:

- the slab was selected due to its sensitiveness to the concrete cover variation, in which a small increase in the cover thickness represents a significant percentage of the structural element cross-section, and it represents the most of the mass of the load-bearing building structures, and by optimizing them, it is possible to achieve the highest savings (Ženíšek et al., 2020);
- the slab area of 4 m × 4 m and being simply supported is representative of slabs used in massive slab projects, as they allow a compensation for larger spans (ranging from 5 to 7 m in length, which demand more significant thickness) and other different support conditions (e.g. fixed supports, which enable smaller thickness). The 4 m spacing make sense to design only from concrete of lower strength classes (Ženíšek et al., 2020);
- a thickness of 12 cm is the minimum standard thickness in terms of structural, thermal and acoustic performance;
- residential building types account for the majority of existing buildings;
- the indoor sheltered from rain is the most damage situation for carbonation;
- the nominal covers from 15 mm to 30 mm are the standard range designed for the city of Porto Alegre;
- the 30 MPa concrete, CA60 steel bars and wooden formworks are usually specified for this type of structure and are widely commercialized in Porto Alegre.

After structure nominal thickness variation definition, the evaluation is performed according to the following steps (Fig. 1):

- dimensioning the element, according to NBR 6118 (Associação Brasileira de Normas Técnicas, 2014) to obtain the reinforcement ratio and, consequently, the material consumption;
- predict the service life (SL), according to Possan et al. (2020), to quantify the structure's durability;
- assess the environmental and economic potential impacts, through a Life Cycle Assessment (LCA) according to ISO 14040 (International Organization for Standard, 2006) and ISO 14044 (International Organization for Standard, 2006), and Life Cycle Cost (LCC) according to BS ISO 15686–5 (British Standard, 2008) and BS EN 16627 (British Standard, 2015b), following the dimensioning and the predicted SL, to obtain the impacts per year.

An economic validation is not performed in this study, the comparison with other works only considers environmental impacts. This limitation can be addressed in future studies.

2.1. Dimensioning

According to the Limit State Methods, the structural element is dimensioned by the structural software Eberick, version 9 (Eberick Software, 2017). The parameters established are in the local standard for reinforced concrete structures project NBR 6118 (Associação Brasileira de Normas Técnicas, 2014), and the software checks both Ultimate Limit State (ULS) and Serviceability Limit State (SLS).

According to the Brazilian standard of loads for the building structures (Associação Brasileira de Normas Técnicas, 1980), 25.0 kN/m^3 of apparent specific weight (reinforced concrete), 1.2 kN/m^2 of coating (6 cm thickness of subfloor and ceramic coating), and a vertical loads of 1.5 kN/m^2 were considered. The combination coefficients used to design the slab for ULS (Equation (1)) and SLS (Equation (2)), and the element was dimensioned for a design bending moment of 6.92 kN m/m (Fig. 2). The variation occurs only in the cover to reinforcement, from 15 mm to 30 mm, composing four different scenarios.

$$F_{d(ULS)} = 1.4 * (25.0 * 0.12) + 1.4 * 1.2 + 1.4 * 1.5 = 7.98\ kN \,/\, m^2 \tag{1}$$

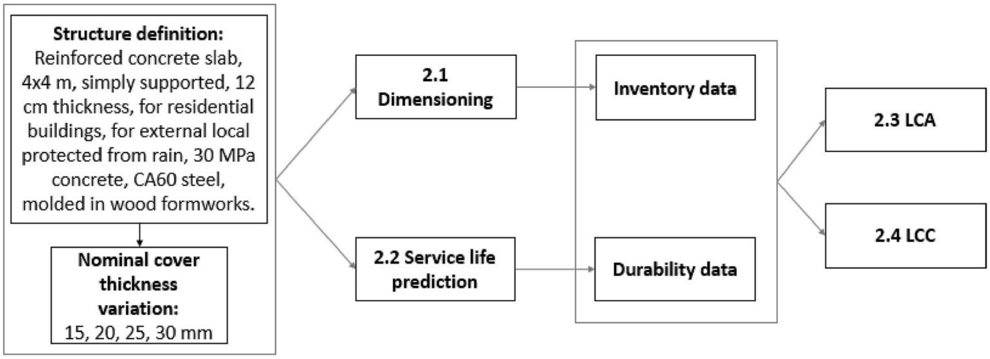


Fig. 1. A general framework of the study. Numbers indicate the sessions where each step is described.

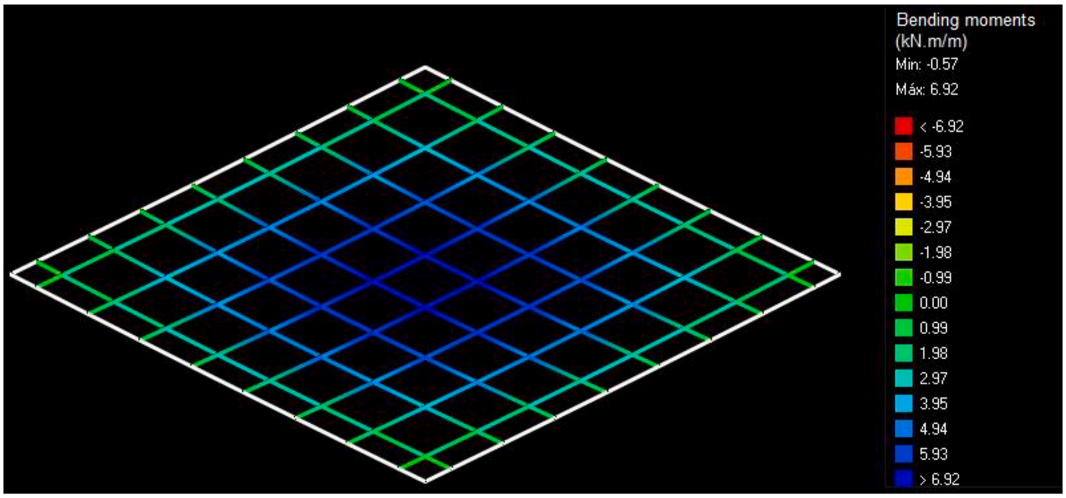


Fig. 2. Slab deformation state (bending moments).

$$F_{d(SLS)} = 1.0 * (25.0 * 0.12) + 1.0 * 1.2 + 1.0 * 0.4 * 1.5 = 5.70\ kN / m^2 \quad (2)$$

Where:

$F_{d(ULS)}$ = design load for Ultimate Limit State (ULS) dimensioning.

$F_{d(SLS)}$ = design load for Serviceability Limit State (SLS) dimensioning.

Designers can adopt higher thicknesses of slabs (15 or 18 cm) when working with larger covers, from a practical perspective. However, varying the cross-section leads to a change in the slab resistance, so it was decided to keep it constant and work with only one variable: the reinforcement ratio.

2.2. Service life prediction

The service life models predicts a structure's expected life based on considerations of environmental conditions, cover thickness, and concrete quality (Mackechnie and Alexander, 2002). The models address one main mechanism for reinforcement depassivation, and concrete carbonation is the most significant in cities away from the coast.

The model selected (adapted in Equation (3)) was developed by Possan (2010) and posteriorly published by Possan et al. (2020). It is based on carbonation depth, and employs simple and easily obtained information without requiring previous tests. Furthermore, the simulation is conducted simply via deterministic (not probabilistic) processes, and the method is calibrated and proven for Brazilian conditions.

This study considers, for service life prediction, the information provided by a sizeable local concrete industry for the concrete characteristics, and takes the climate conditions of Porto Alegre into account for the environment. Thus, a concrete strength of 30 MPa was adopted, produced with cement CPIIF (equivalent II ASTM C 150 and CEM II EN 197–1), with 7.5% of pozzolan addition. Environmental conditions are CO_2 content of 405 ppm (National Oceanic and Atmospheric Administration, 2018), 76.5% relative humidity, of Porto Alegre's annual average (Instituto Nacional De Metereologia, 2018), and indoor exposure sheltered from the rain. The carbonation depth considered to achieve the time initiation for carbonation-induced reinforcement corrosion (the end of the service life predicted) is the projected cover.

$$t = \left(\frac{Cover}{k_c . \left(\frac{20}{f_c}\right)^{k_{fc}} .\exp\left[\left(\frac{k_{ad} .ad^{\frac{3}{2}}}{40+f_c} \right) + \left(\frac{k_{CO_2} .{CO_2}^{0,5}}{60+f_c} \right) - \left(\frac{k_{RH} .(RH-0.58)^2}{100+f_c} \right) \right] .k_{ce}} \right)^2 .20 \quad (3)$$

Appendix B lists data coefficients required for the method application. Those used in this study are:

Cover = average concrete carbonation depth (varied from 15, 20, 25 and 30 mm);

f_c = concrete compressive strength, in MPa (for the study f_c = 30 MPa);

k_c = variable factor regarding the cement type used (for cement CPIIF, $k_c = 21.68$);

k_{fc} = variable factor regarding concretes compressive strength, in function of used cement type (for Brazilian cement CPIIF, $k_{fc} = 1.50$);

t = concrete age, in years (calculated as function of project cover);

ad = pozzolanic addition content in concrete, in % related to cement mass (for the study ad = 7.5);

k_{ad} = the variable factor regarding pozzolanic addition in concrete – silica fume, metakaolin and rice husk ash – in function of used cement type (for cement CPIIF, $k_{ad} = 0.24$);

RH = relative humidity, in %*0.01 (for the study UR = 0.765);

k_{RH} = variable factor regarding relative humidity, in function of used cement type (for Brazilian cement CPIIF, $k_{RH} = 1100$);

CO_2 = CO_2 content in the atmosphere, in % (for the study $CO_2 = 0.0405$);

k_{CO_2} = variable factor regarding environment CO_2, in function of used cement type (for Brazilian cement CPIIF, $k_{CO_2} = 18$);

k_{ce} = variable factor regarding the rain protection, in function of structures exposure conditions (for indoor, sheltered from rain, $k_{ce} = 1.30$).

The model was validated using 298 data points of the natural carbonation available in the literature, representing 87% of tested data, obtained the determination coefficient of 0.9860, and the root-mean-square error (RMSE) of 0.3 mm (Possan et al., 2020).

2.3. Life cycle assessment (LCA)

LCA is developed according to ISO 14040 (International Organization for Standard, 2006) and ISO 14044 (International Organization for Standard, 2006), and it is performed in openLCA 1.6.3 software (openLCA, 2018) along with ecoinvent 3.3 database (ecoinvent, 2018), whose system model adopted is "allocation, cut-off by classification".

2.3.1. Goal and scope definition

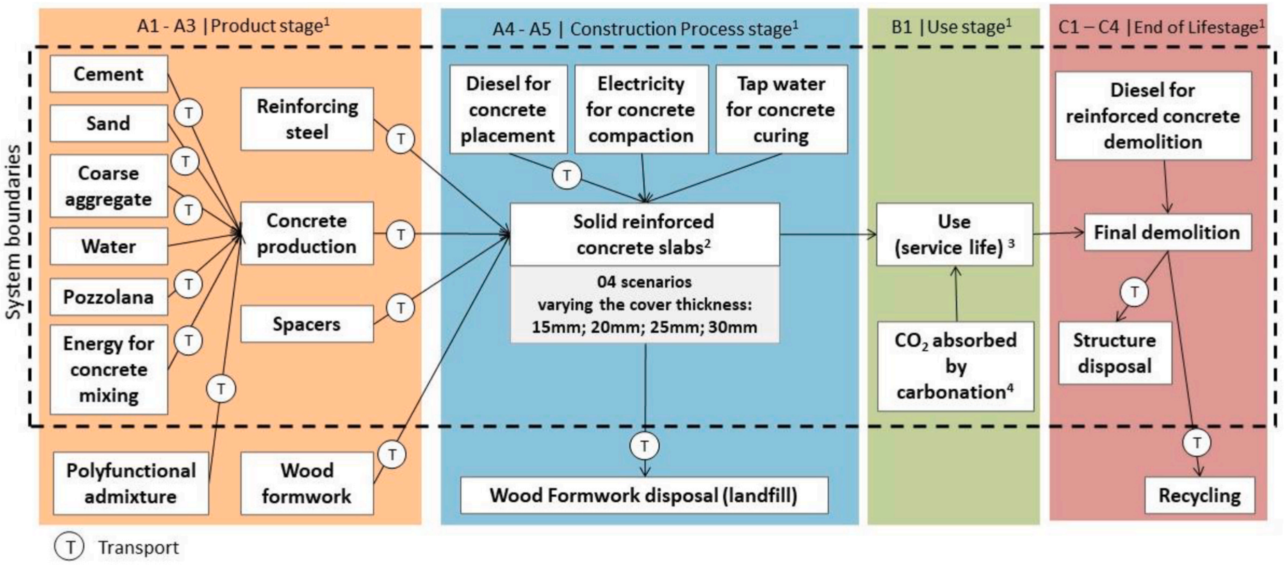
The LCA objective is to evaluate and compare the environmental impacts from cradle to grave of one structural element (slab) of reinforced concrete, per service life year predicted, considering changes in materials consumption and durability caused by variations in cover thickness (15, 20, 25, 30 mm), across normalized values.

The product system and boundaries are represented in Fig. 3, following the building life cycle stages, according to BS EN 15978 (2011).

During the product stage (Modules A1 to A3), the present study considers material production and the services used throughout construction. The required materials for the evaluated system are reinforcing steel, concrete, and spacers. The analysis does not include wood formworks and the use of a polyfunctional admixture in concrete production. Chemical substances used in concrete admixtures could be a concern when considering their toxicological properties, although these environmental impacts are rarely included in published inventories of concrete production (Petek Gursel et al., 2014). The polyfunctional admixture is not considered because there is no dataset available, and the quantity is almost the same for the scenarios analyzed. Finally, formworks and their final disposal are out of the system, because their amount is constant, regardless of the scenario assessed.

The construction process stage (Modules A4 and A5) considers the reinforced concrete slab construction within inputs: diesel for concrete placement, electricity for concrete compaction, and tap water for concrete curing. The transport of materials and products from the factory gate to the building and construction equipment are also considered.

During the use stage, the present study considers only the B1 stage (Use) and does not include structure maintenance, because design service life is when concrete structures keep their characteristics without significant interventions (Associação Brasileira de Normas Técnicas, 2014), and the standard NBR 15575 (Associação Brasileira de Normas Técnicas, 2013) considers the structure as a non-maintainable building part. The service life predicted considers the use stage period, when the



[1] Building life cycle stages according to BS EN 15978 (2011);

[2] Functional equivalent: solid concrete slabs with dimension of 4x4 meters, with 12 cm thickness, simply supported, dimensioned for residential buildings, composed of a 30 MPa commercial concrete, CA60 steel (in bars), molded-in wood formworks, vertical loads 1.5 kN/m², 1.2 kN/m² of coating, and apparent specific weight of 25 kN/m;

[3] The years of service life (durability) vary according to the scenario and takes the climate conditions of Porto Alegre into account. Thus, it adopts concrete class 30, produced with cement CPII-F (equivalent II ASTM C 150 and CEM II EN 197-1), with 7.5% of pozzolan addition.

[4] Calculated according to Annex C from BRE Environmental Profiles 2013: Product Category Rules for Type III environmental product declaration of construction products to EN 15804 (BRE, 2013)

Fig. 3. System product of solid reinforced concrete slabs and related stages, according to BS EN 15978 (2011).

slabs absorb CO_2 through the carbonation of CaO present in the concrete, giving the natural effect of concrete carbonation.

The end-of-life stage (Modules C1–C4) is the demolition, transport, and final disposal of the structural components. Doka (2003) proposes different end-of-life models, including sorting and recycling. This model is considered in this study but omits calculations related to recycling. Thus, the processes of disassembly, separation, and transport to the final disposal site are addressed. The recycling of concrete and reinforcing steel is not in the present study and can be explored in future research.

2.3.2. Inventory analysis

The primary data (concrete volume and steel weight) are from the slabs dimensioning and are used to calculate the quantities of other materials. As previously mentioned, formworks are not considered. The quantification of the other materials is according to the conversion table in Table 1.

For the spacer quantity, which are used to position the reinforcement to obtain the concrete cover projected, it is considered a 1.33 unit per kg of reinforcement obtained in the dimensioning (Caixa Econômica Federal, 2019). For demolition, it is considered 0.33 kWh per m^3 of structure, according to Rohden and Garcez (2018).

The quantitative data calculated from the structure dimensioning is presented in Table 2.

2.3.3. Impact assessment

Environmental impact evaluation is based on the categories mentioned in EN 15804 (Comité Européen de Normalisation, 2013), all from CML 4.4 baseline 2015 (Acero et al. 2017): (i) Climate change – GWP-100; (ii) Acidification potential – AP; (iii) Eutrophication – generic EP; (iv) Photochemical oxidation - POCP; (v) Ozone layer depletion – ODP; (vi) Depletion of abiotic resources – not fossil – ADPN; (vii) Depletion of abiotic resources – fossil – ADPF.

The impacts of the concrete carbonation are according to EN 15804 (BRE, 2012). This study considers the parameters of Group 1, low strength concrete. The amount of carbonation (kg) per m^3 of concrete (i.e., amount of CO_2 reabsorbed through carbonation) is based on the percentage of CaO, which will carbonate, and the amount of CaO within the product. It was assumed that the total concrete cover depth carbonates within the building's lifetime through the element exposed area. Equation (4) illustrates this:

$$Carbonation\left(\frac{kg}{m^3}\right) = 0.63xQ_{Cem}x\%C_{Cem}x0.65x\left(\frac{44}{56}\right) \tag{4}$$

The data coefficients used are recommended by EN 15804 (BRE, 2012):

Carbonation = mass of CO_2 absorbed per m^3 of structure;

Q_{Cem} = amount of cement in the concrete (for this study 316 kg/m^3);

$\%C_{Cem}$ = percentage of clinker in cement (for this study 0.8).

The total mass of CO_2 absorbed for the different cover thickness scenarios is calculated by multiplying the carbonation ratio for surface area and depth of carbonation (Table 3).

2.4. Life Cycle Cost assessment (LCC)

The LCC evaluates the cost of a building (or its parts) over its life cycle while meeting technical and functional requirements (British Standard, 2015b). The calculation is according BS ISO 15686–5 (British Standard, 2008) and BS EN 16627 (British Standard, 2015b).

Cost assessment started with the dimensioned data. Prices of required inputs (materials, labor and equipment) are from the Brazilian National System of Civil Construction Costs and Indexes Research - SINAPI (Caixa Econômica Federal, 2019). The table cost is from January 2019 for Porto Alegre. In the absence of tabulated costs, a survey made in the regional market provided the values. The values considered are current with no correction to future costs such as demolition and disposal.

The other definitions of the LCC are the same as those defined for the LCA. It is important to emphasize that the LCC study is not an environmental accounting, and the goal is different from the LCA study (Gluch and Baumann, 2004). However, both studies scope definitions aligned in the present study by considering the same inventory data and the same life cycle stages.

Table 1
Relation and conversion of materials considered to quantification.

Comparison Relation	Conversion			Reference
	Quantity	Unit	Material	
1 m^3 of concrete	316.00	kg	Cement	Local concrete industry
	79.00	l	Pozzolan	Local concrete industry
	741.00	kg	Sand	Local concrete industry
	1145.00	kg	Coarse aggregate	Local concrete industry
	189.60	kg	Water	Local concrete industry
	1.94	kWh	Concrete mixing energy	Caixa Econômica Federal (2019)
	0.12	kWh	Compaction energy	Caixa Econômica Federal (2019)
	5.00	kWh	Diesel for pumping	Rohden and Garcez (2018)
	2400.00	kg	Final disposal	Estimated
	500.00	kg	Water for concrete cure	Estimated

3. Results and discussion

3.1. Dimensioning and service life prediction

Table 4 shows the results of slabs dimensioning and their predicted service life.

The increase in concrete cover (from 15 mm to 30 mm) leads to a rise of 16.27% in steel consumption and a non-significant reduction in concrete consumption. It was expected, since the increase in cover thickness leads to a decrease in the useful reinforcement height in the structure dimensioning, demanding more reinforcement to support the same actions. Formworks consumption is constant.

Similarly, an increase in concrete cover promotes growth in structure durability (service life) of 400%. Segura et al. (2016) presented a similar performance while assessing the roof girder service life, with different covers.

The standards usually require, as a normal structure service life, a minimum period of 50 years, but some standards (Comité Européen de Normalisation, 2004; New Zealand Standard, 2006; Japan Society of Civil Engineers, 2007; Instrucción de Hormigón Estructural, 2011) can require 100 years, so these covers studied include all the standards' possibilities. The service life required is usually related to the structure's significance. The more important a structure, more service life is

Table 2
Quantitative data used to LCA, calculated according to the structure dimensioning.

Process	Output	Input	Unit	Cover (mm)			
				15	20	25	30
Materials production	Concrete	Cement	kg	517.39	517.31	517.23	517.11
		Pozzolan	l	129.35	129.33	129.31	129.28
		Sand	kg	1213.25	1213.06	1212.88	1212.59
		Coarse aggregate	kg	1874.73	1874.44	1874.15	1873.71
		Water	kg	310.44	310.39	310.34	310.27
		Energy for concrete mixing[a]	kWh	3.18	3.18	3.18	3.18
	Reinforcement	Steel	kg	43.09	45.09	47.10	50.10
	Spacers	Plastic spacers	unit	57.31	59.97	62.64	66.64
Reinforced concrete structure construction	Pumping	Diesel for concrete placement	kWh	8.19	8.19	8.18	8.18
	Compaction	Electricity medium volt for concrete compaction	kWh	0.19	0.19	0.19	0.19
	Curing	Tap water for concrete curing	kg	818.66	818.53	818.40	818.21
End-of-life	Demolition	Diesel for reinforced concrete demolition	kWh	545.34	545.34	545.34	545.34
	Final disposal	Concrete	kg	3929.56	3928.95	3928.34	3927.42
		Steel	kg	43.09	45.09	47.10	50.10

[a] Value according Caixa Econômica Federal (2019) in Table 1.

Table 3
Mass of carbonation for the different cover thickness scenarios.

Cover (mm)	Depth of carbonation (m)	Surface area (m^2)	Carbonation ratio (kg/m^3)	Carbonation (kg)
15	0.015	13.69	81.34	16.70
20	0.020			22.27
25	0.025			27.84
30	0.030			33.41

required.

Despite the benefits that the cover provides to the structure durability, cover thickness in excess (more than those assessed) increases the possibility of fissures (March, 2003) as the width of the cracks in tensile zones grows significantly (Navarro et al., 2018).

The correct design and execution of the concrete cover are essential. To ensure an acceptable design service life for a standard minimum of 50 years, a minimum cover of 20 mm is required for carbonation. For a 100 years standard service life, a minimum cover of 30 mm is required, according to the service life prediction method. However, the standards recommend adding an execution tolerance to the minimum cover, which usually depends on the execution control level adopted in the structure construction stage. This tolerance could be 5–10 mm (Associação Brasileira de Normas Técnicas, 2014), 0–10 mm (Bureau of Indian Standards, 2000; Instrucción de Hormigón Estructural, 2011; Comité Européen de Normalisation, 2004), 10–13 mm (American Concrete Institute, 2014), 5–15 mm (Japan Society of Civil Engineers, 2007; Deutsche Norm, 2008; British Standard, 2015a), where more control means that less tolerance is necessary, allowing a smaller nominal cover design to be possible.

3.2. Environmental assessment

Fig. 4 shows a comparison of each life cycle stage in potential environmental impacts for each concrete cover.

With the increase in the cover thickness increased the total incorporated environmental impacts. This increment justifies by the higher consumption of some materials in the structure dimensioning, such as the steel reinforcement (16.27%) and plastic spacers.

Concerning the higher impact stage, material production is outstanding, followed by the end-of-life. Construction impacts are insignificant compared to the other stages, so Rohden and Garcez (2018), Ede et al. (2014), Pretot et al. (2014), Paik and Na (2019), Ferreiro-Cabello et al. (2016), Ferreiro-Cabello et al. (2017) also pointed it as mainly responsible for the environmental impact over the structure's life cycle. This tendency can change when considering some maintenance in the use stage, such as recurring energy consumption by repair strategies for corrosion and seismic activity (Yu et al., 2020). In this case, the use stage accounted for climate change due to CO_2 absorption related to concrete carbonation. As expected, the increase in cover thickness raises the depth of carbonation, and the avoided climate change impacts.

The end-of-life stage has a considerable impact, because the principal inputs are related to the transport and final disposal of concrete and steel residues. The modals (freight train and freight lorry) and the distances are the keys responsible for the results. Besides that, the mechanized technique for slab demolition is fed by

Table 4
Dimensioning and predicted service life of the different scenarios.

Dimensioning						Predicted Service Life (years)
Cover (mm)	Steel reinforcement in X	Steel reinforcement in Y	Steel weight (kg)	Concrete volume (m^3)	Formwork (m^2)	
15	22 ϕ6.3 mm c/18 C = 409 cm[a]	21 ϕ6.3 mm c/19 C = 409 cm	43.09	1.64	13.69	27.35
20	23 ϕ6.3 mm c/17 C = 409 cm	22 ϕ6.3 mm c/18 C = 409 cm	45.09	1.64	13.69	48.62
25	24 ϕ6.3 mm c/16 C = 409 cm	23 ϕ6.3 mm c/17 C = 409 cm	47.10	1.64	13.69	75.96
30	26 ϕ6.3 mm c/15 C = 409 cm	24 ϕ6.3 mm c/16 C = 409 cm	50.10	1.64	13.69	109.38

[a] Representation for: 22 bars of 6.3 mm diameter spaced transversely every 18 cm, possessing 409 cm of length each.

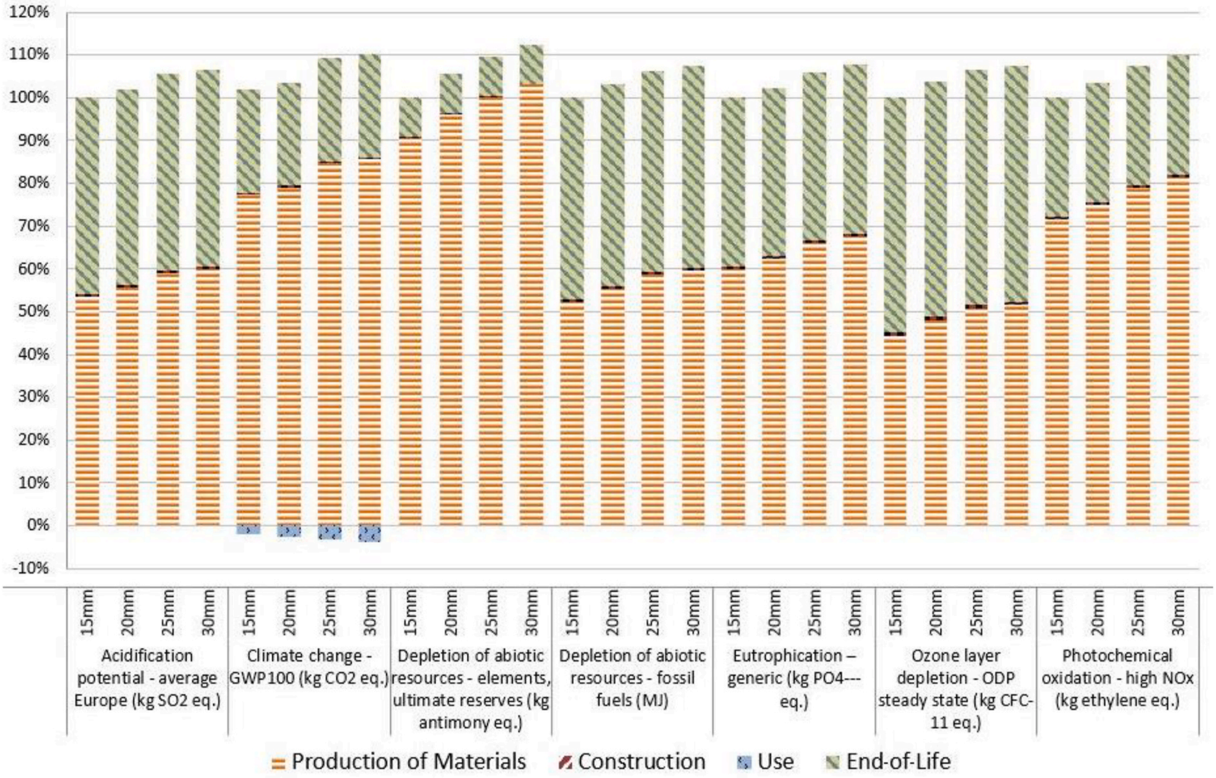


Fig. 4. Comparison of the total environmental impacts for the different scenarios of cover thickness, considering 15 mm as a base scenario.

diesel, and the fuel quantity considered represents another substantial part of the environmental impact. Hackenharr et al. (2019) showed that the end-of-life scenario for construction and demolition waste, recycling and reuse analysis are different considering allocation procedures, directly affecting the LCA results.

Fig. 5 shows the participation of each material, in percentage, in the life cycle. This assessment does not consider 15 mm as a base scenario, and the material proportion of the environmental impacts sums 100%.

The concrete production presented the highest impacts for all categories within the materials production stage, especially for climate change. The exception occurs for photochemical oxidation potential and depletion of non-fossil abiotic resources, which is more representative for steel production. Habert et al. (2012) evaluated the environmental consequences of the use of high-performance concrete instead of traditional concrete for a bridge from cradle-to-grave, and found similar results for the materials production stage, where concrete presented the highest impacts for acidification, eutrophication, global warming, and ozone layer depletion, and steel was predominant for ecotoxicity indicators.

The cement production and steel are the main contributors to many environmental impacts in structures of conventional concrete (Paik and Na, 2019) and the production of steel and concrete has a higher embodied energy than the other materials as found by Buyle et al. (2013) and Yu et al. (2020).

Another material that contributes to the materials production stage impacts is the coarse aggregate in concrete production, especially in the depletion of abiotic resources, varying between 21.61% (15 mm cover) to 19.20% (30 mm cover). Some studies, as Van Den Heede et al. (2012) and Wu et al. (2014), indicate it as the second-largest contributor in concrete production. For this reason, some researches explore how to reduce these impacts by replacing coarse aggregate with waste materials. The recycling practice can be successfully implemented in concrete technology, yielding an effective way to convert industrial waste products into raw resources to produce new materials, support construction waste management, and aid construction stakeholders' in making sustainable decisions (Napolano et al., 2016).

Some materials production does not represent significant potential impacts, like the sand and tap water in the production stage – under 5% and 0.1% in all impact categories, respectively - or the tap water in the construction process stage – under 3%. However, even reduced impacts or parts of the concrete system that are deemed insignificant can add up when considering global production (Petek Gursel et al., 2014).

For the construction stage, diesel for concrete pumping presented the highest impacts for all categories, except for concrete water cure, which presented higher non-fossil abiotic resources depletion potential.

Ferreiro-Cabello et al. (2016) investigated the CO_2 emissions and costs generated by constructing structures with flat slabs depending on the column layout and slab thickness. They found that for a structure with a slab span of 5 m, the production stage represents 89.84% of the kgCO2eq/m2, and the construction stage 10.16%. If this present study considers the same two stages of the life cycle, the results will vary slightly, with the production stage representing almost 99% and the construction stage only 1% in all scenarios. These results are related to the considerations of transport, and Buyle et al. (2013) point that in LCA studies on buildings, a frequent conclusion is the minor importance of

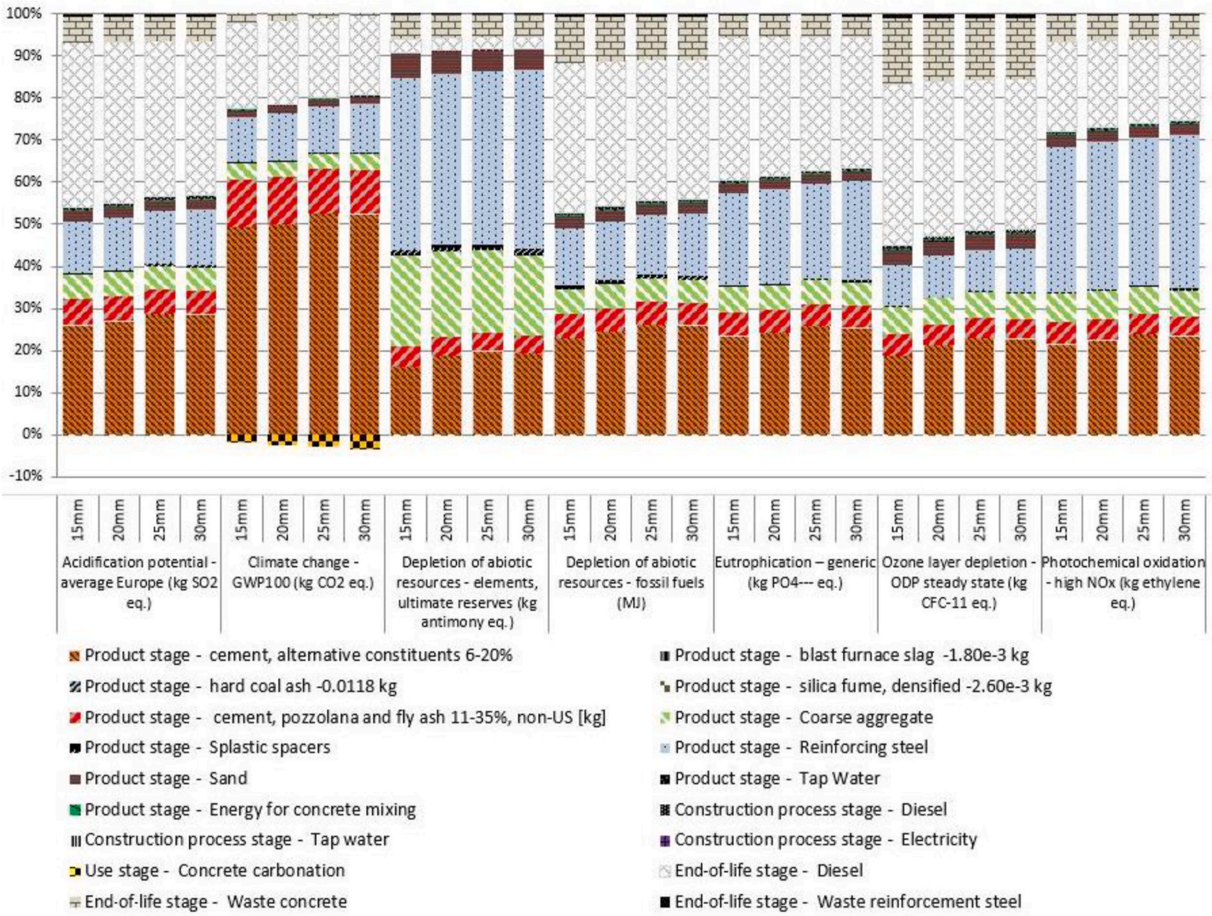


Fig. 5. Environmental impacts by materials and stages of structural element (slab) for the different scenarios of cover thickness.

Table 5
Results for the life cycle costs of slabs with different concrete covers.

Description	Unit	Unit Price	Cover (mm)			
			15	20	25	30
			Total Price	Total Price	Total Price	Total Price
Manufacture of slab formwork, made of resin plywood 17 mm.	m^2	USD 7.32	USD 100.25	USD 100.25	USD 100.25	USD 100.25
Assembly and dismantling of massive slabs formwork with average areas less than or equal to 20 m^2, single sided, made of resin plywood, 2 uses.	m^2	USD 9.82	USD 134.46	USD 134.46	USD 134.46	USD 134.46
Slab frame of conventional reinforced concrete structures in multi-stored building using CA50 steel.	kg	USD 2.07	USD 89.07	USD 93.21	USD 97.36	USD 103.57
Concreting slabs, with use of pump in building with average areas of slabs less or equal to 20 m^2 - launching, densification and finishing (concrete included).	m^3	USD 104.10	USD 170.45	USD 170.42	USD 170.40	USD 170.36
Humidification with 10000l kite truck.	m^2	USD 0.32	USD 0.26	USD 0.26	USD 0.26	USD 0.26
Demolition of slabs mechanized, with no reuse.	m^2	USD 28.93	USD 47.53	USD 47.53	USD 47.53	USD 47.53
Final disposal of rubble (structure + formwork).	m^3	USD 12.92	USD 47.76	USD 47.76	USD 47.76	USD 47.76
Total Cost			USD 589.78 100.00%	USD 593.90 100.70%	USD 598.02 101.40%	USD 604.19 102.44%
Cost/Year			USD 21.57 100.00%	USD 12.22 56.64%	USD 7.87 36.50%	USD 5.52 25.61%

*Exchange 1 USD = R$ 3.87 (January/2019).

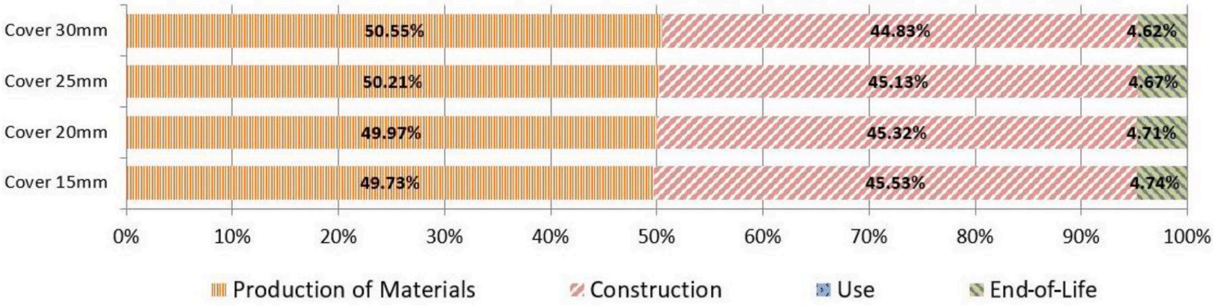


Fig. 6. Total costs of structural element (slab) for the different scenarios of cover thickness, considering 15 mm as a base scenario.

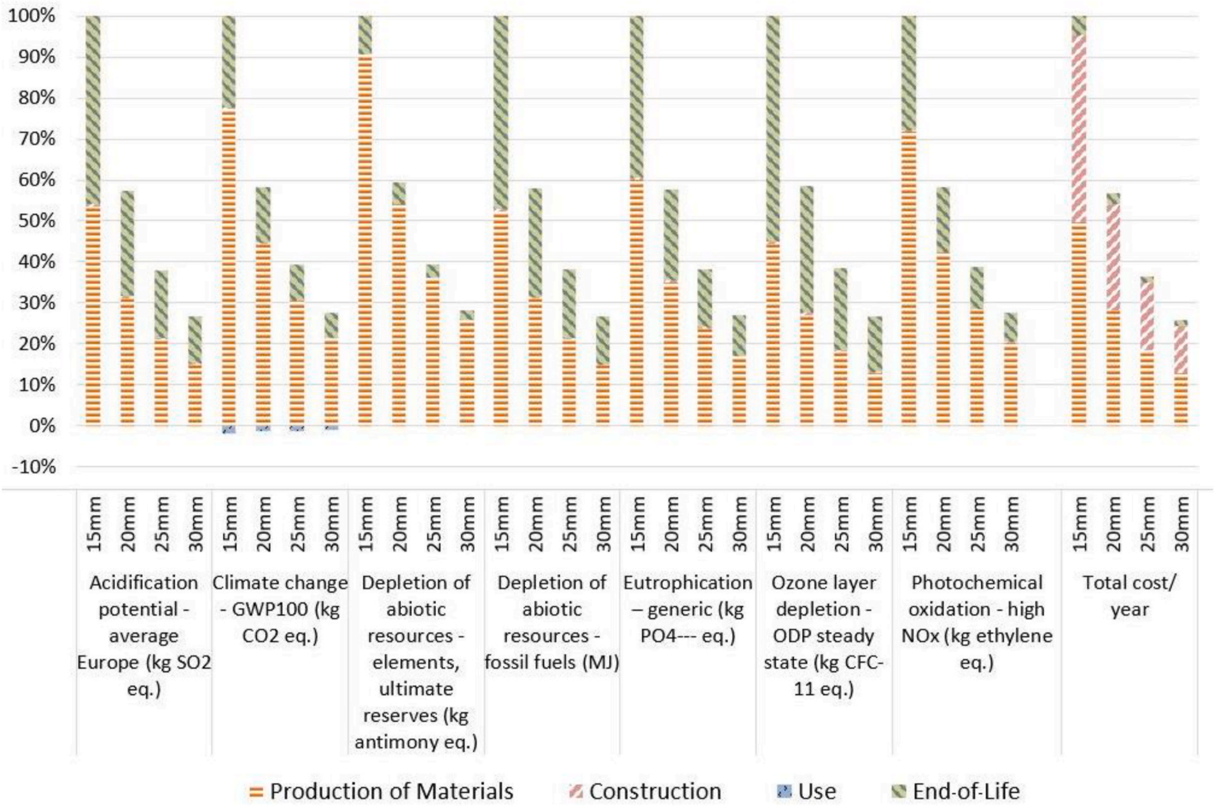


Fig. 7. Comparison between the environmental impacts and the costs per stage and year of predicted service life for each scenario analyzed.

the transportation of materials compared to the other stages.

For the end-of-life scenario, market processes are considered for the treatment and disposal of non-hazardous waste like reinforcement steel and concrete, considering the works for deconstruction, transport, and final disposal of the structure. In this way, 100% of the structure is demolished using diesel and the waste is disposed of in a landfill. For the end-of-life stage, diesel for structures demolition causes the most impact in all categories. The same is highlighted by Martínez et al. (2013) that compared two buildings' end-of-life scenarios, and indicated that waste transport is the environmental aspect with a higher relative contribution to life cycle impact. The authors also pointed out that the end-of-life management plan choice, selective demolition, or conventional demolition can considerably affect some environmental indicators, e.g., GWP kgCO2eq with 89% of the difference between the results (Martínez et al., 2013). The present study considers the selective demolition, separating concrete and steel parts to the final disposal.

3.3. Economic evaluation

Table 5 shows the total cost per slabs with different covers, which was divided per year of predicted service life, and a percentage of comparison was showed, considering the 15 mm concrete cover as a reference.

It is possible to observe an increase of 2.44% in total incorporated costs, with the increase in cover (smallest to most extensive). The cost rise was expected once the material consumption increased and would occur at the same proportion, which did not happen, showing an insignificant increment.

However, when considering the durability, the increase in cover thickness reduces the costs up to 74.39% per year of predicted service life. It is important to note that although the formworks are not in the life cycle assessment (LCA) system boundaries, they are in the budget due to their costs' significant representativeness.

This analysis is fundamental in the decision-making processes since it considers the life cycle perspective to analyze the economic and environmental acquisitions. In this way, it is possible to recognize that some solutions, identified as cheaper in the short and medium-term, can present high costs and impacts of maintenance and final disposal at the end of their useful life (Bribián et al., 2011).

Fig. 6 shows the cost participation of each stage, in percentage, in the structure life cycle. In this figure, the assessment does not consider 15 mm as a base scenario, and the cost proportion sums 100%.

The costs present similar environmental impacts trends, the total amount increases with the cover enlargement, however the cost stages with more substantial participation are materials production followed by construction and then the end-of-life.

3.4. Comparative between predicted service life, LCA and LCC

Fig. 7 compares the environmental impacts and the costs per stage and year of predicted service life, considering the 15 mm concrete cover as a reference.

The concrete cover thickness increase results in a lower environmental impact on a reinforced concrete structure's life cycle because the predicted service life is higher (about 400%) than the increase in material consumption (16.27%). Impacts per year of service life predicted a reduction from 72.52% (Photochemical Oxidation Potential – POCP) to 73.15% (Ozone Layer Depletion Potential – ODP) from the smaller to the more extensive cover.

Navarro et al. (2018) compared the environmental performance of prestressed reinforced concrete structures (concrete bridges decks) with other equivalent structural solutions (using galvanized reinforcement), and also concluded that an increase in cover thickness could reduce environmental impacts on life cycle in up to 45%, with performance similar to that of other alternatives studied. Although applied in a different but similar structural system, this study corroborates with Navarro et al. (2018) that an increase in cover thickness could significantly reduce the structure life cycle impacts.

A similar performance was observed for costs, in which the disparity between the total cost incorporated (2.44%) and the predicted service life (400%) is much higher.

In this way, the present study's main contribution is that it performs a cradle to grave LCA and LCC. Additionally, the combination of the economic and environmental data is key to better choices in the decision-making process of reinforced concrete structures. Ferreiro-Cabello et al. (2016) enhance this view that reliable information regarding environmental impacts and costs allows planners and engineers to make better and more informed technical decisions.

4. Final remarks

Considering the study results, the cover thickness is a very important item to be considered in reinforced concrete structure as it can significantly impact structural performance.

The increase in the cover thickness of reinforced concrete slabs, from smaller (15 mm) to more extensive (30 mm) implies:

- an increase in steel consumption of 16.27%, keeping the concrete transversal section constant and considering one same structural performance;
- up to a 400% increase in service life predicted of the structure;
- 2.44% increase in total incorporated costs;
- increase in total incorporated environmental impacts for all categories assessed, ranging from 6.46% to 12.51% (due to higher materials consumption).

As expected, the cover influences the material consumption, and consequently the environmental impact, but not at the same proportion. Also, it does not significantly impact the costs. The major cover impingement is, no doubt, in the durability.

While considering service life predicted of each scenario in a life cycle approach, an increase in cover thickness causes:

- up to a 74.39% reduction in costs per year of service life predicted;
- a reduction of up to 73.15% in environmental impact (such as Ozone Layer Depletion Potential – ODP) per year of service life predicted.

Based on a reinforced concrete structure life cycle approach, an increase in concrete cover thickness highlights the structure's durability, reduces costs and environmental impacts per year of predicted service life. Therefore, an increase in concrete cover is more sustainable, both economically and environmentally.

However, precautions must be taken when adopting covers too much higher than those standardized, aiming solely and exclusively at increasing durability. When durability is necessary, in case of special buildings, a combination of an increased cover thickness with an increase in concrete resistance can be utilized. The service life prediction can easily reflect it. Another option is to change the cement type (for cement purer, e.g., CP I or CEM I), or not using pozzolanic addition.

Similarly, the simple cover thickness reduction (a widespread attitude, both in the design stage and in execution) leads to an increase in the costs and environmental impact per year of service life predicted. Therefore, to minimize the harmful effect of reducing cover thickness, it demands changes in the structure's concept in the design phase.

Although some standards permit the reduction of the nominal cover (considering the tolerance execution), it is desirable not to reduce the cover thickness. Designs incorporating an oversized cover thickness can reduce both the costs and environmental impacts that the structure imposes.

Acknowledgements

The authors acknowledge the financial support from CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazilian Federal Agency for Support and Evaluation of Graduate Education) and CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico - National Council of Scientific and Technological Development – Brazil). The participation of Menna Barreto was sponsored by CNPq grant number 142266/2018–3 and CAPES grant number 88882.439905/2019–01; Timm was sponsored by CNPq grant number 429264/2018–6; Passuello was sponsored by CNPq through the research fellowships PQ 2018, grant number 306045/2018–4 and Universal grant number: 429264/2018–6.

Appendix A. Dimensioning

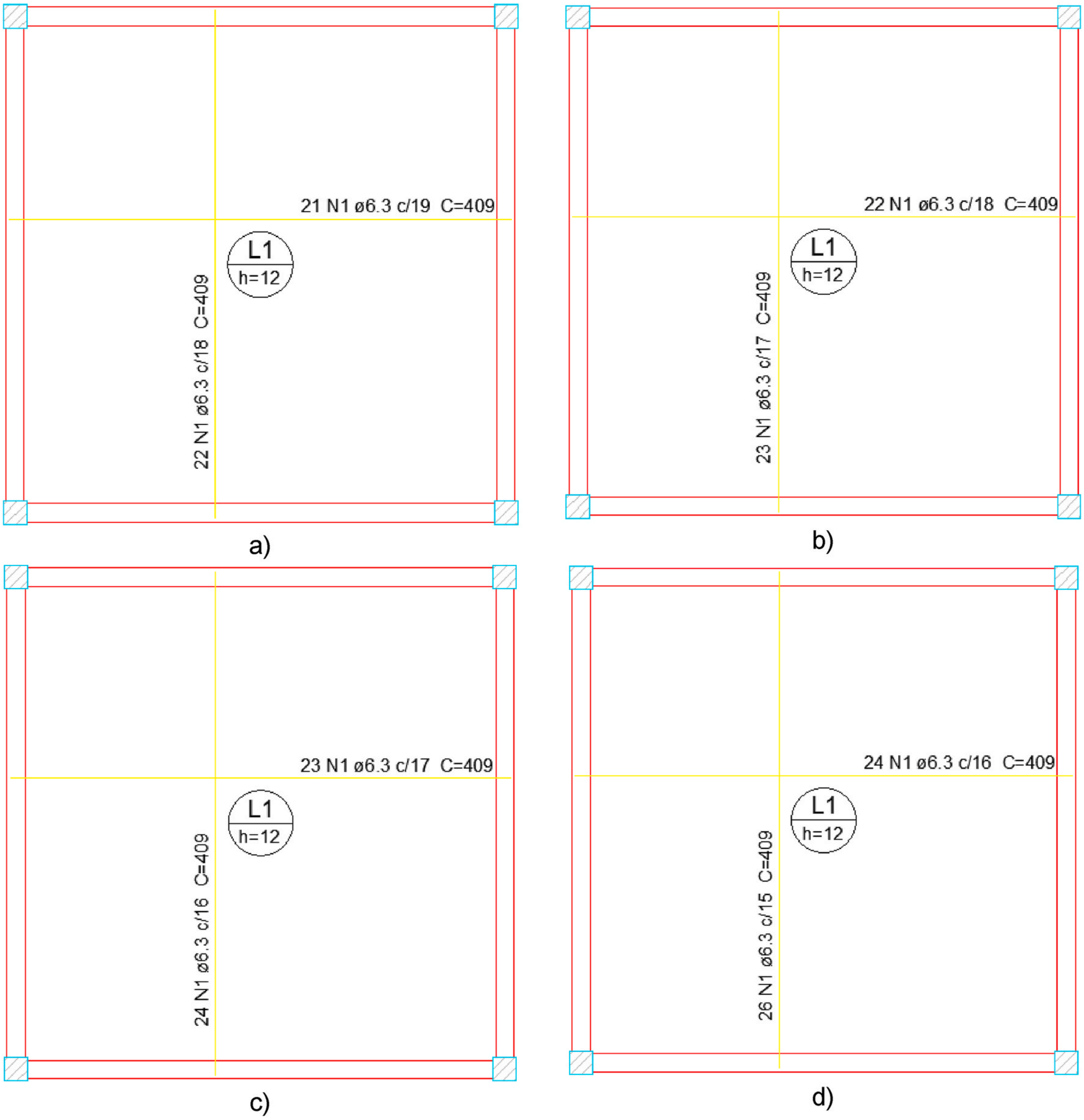


Fig. A.1. Slab structural design for: a) nominal cover of 15 mm; b) nominal cover of 20 mm; c) nominal cover of 25 mm; d) nominal cover of 30 mm

Appendix B. Service Life Prediction

Table B.1
Coefficients of the service life prediction model as a function of concrete characteristics and environmental conditions (Possan, 2010; Possan et al., 2020)

Cement type	Concrete characteristics			Environmental conditions	
	Cement	f_c	Mineral admixture	CO_2	RH
	k_c	k_{fc}	k_{ad}	k_{co2}	k_{RH}
CEM I[1]	19.80	1.70	0.24	18.00	1300
CEM II/A-L[2]	21.68	1.50	0.24	18.00	1100
CEM II/A-S[3] CEM II/B–S[3]	22.48	1.50	0.32	15.50	1300
CEM II/A-V[4]	23.66	1.50	0.32	15.50	1300
CEM III/A[5]	30.50	1.70	0.32	15.50	1300
CEM IV/A[6], CEM IV/B[6]	33.27	1.70	0.32	15.50	1000

[1] Ordinary Portland Cement - Equivalent at Brazilian Cement CP I and CP V/ASTM C 150.

[2] Portland cement with limestone filler - Equivalent at Brazilian Cement CP II F/ASTM C 150.

[3] Portland cement with slag - Equivalent at Brazilian Cement CP II E/ASTM C 595/IP.

[4] Portland cement with pozzolan - Equivalent at Brazilian Cement CP II Z/ASTM C 595/IS.

[5] Portland cement with slag - Equivalent at Brazilian Cement CP III/ASTM C 595.

[6] Portland cement with pozzolan - Equivalent at Brazilian Cement CP IV/ASTM C 595.

Table B.2
Coefficients of the service life prediction model as a function of structure exposure condition (Possan, 2010; Possan et al., 2020)

Structure exposure conditions	Coefficient (k_{ce})
Indoor, sheltered from rain	1.30
Outdoor, sheltered from rain	1.00
Outdoor, exposed to rain	0.65

Appendix C. Life Cycle Assessment (LCA)

Table C.1
Data reference for the inventory analysis

Input	Reference process/flow unit	Geography/ Year	Source
Cement	market for cement production, alternative constituents 6–20%	RoW/2009	Ecoinvent 3.3
Sand	market for sand/sand [kg]	GLO/2011	Ecoinvent 3.3
Pozzolan	market for cement, pozzolan and fly ash 11–35%	GLO/2009	Ecoinvent 3.3
Coarse aggregate	market for gravel, crushed/gravel, crushed [kg]	RoW/2011	Ecoinvent 3.3
Water	market for tap water/tap water [kg]	RoW/2012	Ecoinvent 3.3
Energy for concrete mixture and compaction	market for electricity, medium voltage/electricity, medium voltage [kWh]	GLO/2017	Ecoinvent 3.3
Spacers	market for polyethylene terephthalate, granulate, bottle grade/polyethylene terephthalate, granulate, bottle grade [kg]	GLO/2011	Ecoinvent 3.3
Steel reinforcement	market for reinforcing steel/reinforcing steel [kg]	GLO/2011	Ecoinvent 3.3
Diesel for concrete laying	market for diesel, burned in building machine/diesel, burned in building machine [MJ]	GLO/2011	Ecoinvent 3.3
Diesel for concrete demolition	machine operation, diesel, < 18.64 kW, high load factor/diesel, burned in building machine [MJ]	GLO/2014	Ecoinvent 3.3
Final disposal of concrete	market for waste concrete/waste concrete [kg]	GLO/2011	Ecoinvent 3.3
Final disposal of steel	market for waste reinforcement steel/waste reinforcement steel [kg]	GLO/2011	Ecoinvent 3.3

Table C.2
Life Cycle Impacts Assessment (LCIA) per stage, scenario and impact

Impacts	Life Cycle Stage				
	Materials Production (A1-A3)	Construction (A4-A5)	Use (B1–B7)	End-of-life (C1–C4)	Total
Acidification potential - average Europe (kg SO_2 eq.)					
Cover 15 mm	1.89E+00	2.44E-02	0.00E+00	1.62E+00	3.53E+00
Cover 20 mm	1.96E+00	2.44E-02	0.00E+00	1.62E+00	3.61E+00
Cover 25 mm	2.08E+00	2.44E-02	0.00E+00	1.62E+00	3.73E+00
Cover 30 mm	2.11E+00	2.44E-02	0.00E+00	1.62E+00	3.76E+00
Climate change - GWP100 (kg CO_2 eq.)					
Cover 15 mm	6.93E+02	3.39E+00	−1.67E+01	2.17E+02	8.97E+02
Cover 20 mm	7.09E+02	3.39E+00	−2.23E+01	2.17E+02	9.07E+02
Cover 25 mm	7.61E+02	3.39E+00	−2.78E+01	2.17E+02	9.54E+02
Cover 30 mm	7.68E+02	3.39E+00	−3.34E+01	2.17E+02	9.55E+02
Depletion of abiotic resources - elements, ultimate reserves (kg antimony eq.)					
Cover 15 mm	8.66E-04	1.90E-06	0.00E+00	8.80E-05	9.56E-04
Cover 20 mm	9.18E-04	1.90E-06	0.00E+00	8.81E-05	1.01E-03
Cover 25 mm	9.57E-04	1.90E-06	0.00E+00	8.82E-05	1.05E-03
Cover 30 mm	9.85E-04	1.90E-06	0.00E+00	8.82E-05	1.08E-03
Depletion of abiotic resources - fossil fuels (MJ)					
Cover 15 mm	3.69E+03	4.51E+01	0.00E+00	3.33E+03	7.06E+03
Cover 20 mm	3.90E+03	4.51E+01	0.00E+00	3.33E+03	7.27E+03
Cover 25 mm	4.14E+03	4.51E+01	0.00E+00	3.33E+03	7.51E+03
Cover 30 mm	4.21E+03	4.51E+01	0.00E+00	3.33E+03	7.58E+03
Eutrophication – generic (kg PO_4 - eq.)					
Cover 15 mm	5.71E-01	6.03E-03	0.00E+00	3.75E-01	9.53E-01
Cover 20 mm	5.94E-01	6.03E-03	0.00E+00	3.75E-01	9.75E-01
Cover 25 mm	6.29E-01	6.03E-03	0.00E+00	3.76E-01	1.01E+00
Cover 30 mm	6.43E-01	6.03E-03	0.00E+00	3.76E-01	1.03E+00

(*continued on next page*)

Table C.2 (*continued*)

Impacts	Life Cycle Stage				
	Materials Production (A1-A3)	Construction (A4-A5)	Use (B1–B7)	End-of-life (C1–C4)	Total
Ozone layer depletion - ODP steady state (kg CFC-11 eq.)					
Cover 15 mm	2.59E-05	4.86E-07	0.00E+00	3.20E-05	5.84E-05
Cover 20 mm	2.81E-05	4.86E-07	0.00E+00	3.21E-05	6.06E-05
Cover 25 mm	2.97E-05	4.86E-07	0.00E+00	3.21E-05	6.23E-05
Cover 30 mm	3.01E-05	4.86E-07	0.00E+00	3.21E-05	6.27E-05
Photochemical oxidation - high NOx (kg ethylene eq.)					
Cover 15 mm	1.20E-01	7.27E-04	0.00E+00	4.66E-02	1.67E-01
Cover 20 mm	1.25E-01	7.27E-04	0.00E+00	4.66E-02	1.73E-01
Cover 25 mm	1.32E-01	7.27E-04	0.00E+00	4.67E-02	1.80E-01
Cover 30 mm	1.36E-01	7.27E-04	0.00E+00	4.67E-02	1.84E-01

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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