# Exploring life cycle-based sustainability indicators for building structural frames in concrete

# *Indicadores de sustentabilidade com base em ciclo de vida para sistemas estruturais em concreto*

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## Abstract

This paper aims at advancing on the validation of indicators of building concrete frames' sustainability from an integrated, life cycle perspective. A case study approach investigates (i) feasibility of comparing sustainability performance of different flooring systems; and (ii) similarity between environmental indicators trends for a typical flooring system and corresponding whole superstructure. Three residential buildings are analyzed, using either prestressed concrete flat (PCF) slabs or reinforced concrete waffle (RCW) slabs and flat beams exposed to a marine environment. SimaPro 7.3 supports calculation of the environmental indicators. Service life estimation is used to ensure functional equivalence and to form a basis for life cycle costing. PCF slabs showed best functional/technical and economic results but were outperformed by RCW slabs' environmental results. Most environmental indicators showed the same trend for both typical floor and whole superstructure.

*Keywords*: concrete, structural frame, flooring system, sustainability assessment, life cycle indicator.

## Resumo

Este artigo objetiva avançar na validação de indicadores de sustentabilidade com base em ciclo de vida de diferentes sistemas de laje, bem como investigar tendências entre indicadores ambientais de um pavimento-tipo e da superestrutura. Três edificações residenciais em lajes nervuradas em concreto armado (RCW) ou lisas protendidas (PCF) são analisadas em ambiente marinho. Indicadores ambientais são calculados com o apoio do software SimaPro 7.3. Estimativa de vida útil é usada para garantir a equivalência funcional e formar uma base para cálculo de custos do ciclo de vida (CCV). Lajes PCF apresentaram melhores resultados técnico-funcionais e econômicos, mas os ambientais foram superados pelas lajes RCW. A maioria dos indicadores ambientais mostrou a mesma tendência no pavimento-tipo e na superestrutura.

*Palavras-chave:* sistema estrutural, laje em concreto; avaliação de sustentabilidade; indicador de ciclo de vida.

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# 1. Introduction

## 1.1 The role of structural frames on whole-building sustainability

Life cycle-based studies have shown the structural frame and envelope as major contributors to material environmental loads of a building (Dobbelsteen; Arets; Linden [1], Dobbelsteen; Arets; Nunem [2], Haapio, Viitaniemi [3], Kellenberger, Althaus [4], Moon [5]). However, most sustainable buildings assessment systems available so far have not given enough attention to service life, durability, and the role played by structural frames. Worth mentioning exceptions are HQE/AQUA (France/Brazil) and CASBEE (Japan), which include measures to minimize structural materials resources and service life extension of the structural frame among their encouraged sustainability strategies (Oliveira et al [6]).

Structural element reuse can lead to reduction of waste and raw material use for future construction, thus close inspection and accurate qualification of structural members must be completed before that. The advantage of reusing a structural component may result in higher initial project costs and reduce the sustainability of the second structure. Designing for multiple intended uses and possible reuse of a structure may have financial advantages, as the owner can define a new use for the building, which in turn extends the service life of its structure (Laefer, Manke [7]).

Another important issue concerning sustainability is durability, for it decisively influences the service life of buildings. Service life of a building and its parts also defines its environmental performance in terms of material usage, once sustainability is given by the ability to fulfill certain (functional) performance requirements, while subjected to degradation factors and necessary maintenance, at the lowest negative impact of that component on the environment (Nunem, Mooiman [8]). As the service life of the structural frame ultimately defines the lifespan and maintenance intensity of the whole building, it affects not only its environmental performance, but its social and economic performances as well.

Life cycle environmental and costs consideration, as well as observance of functional requirements shall be properly balanced and used to support design decision-making.

## 1.2 Indicators and integrated sustainability assessment

Research initiatives for new generations of sustainable buildings assessments state that buildings sustainability level should always be described using indicators. The selection and justification of indicators should be based on clear understanding about the issues of concern and the relevance of building sector to these issues (Häkkinen, et al. [9], CRISP PeBBu [10], Luetzkendorf et al. [11]).

Defined as a parameter or a value derived from parameters, an indicator is used to illustrate the main characteristics of a given object. It should be relevant, measurable and adequate to the analysis (OECD [12]), whilst remaining objective and providing traceable results. Since indicators main functions are quantification, simplification and communication, they can be used for assessment, diagnosis, comparison and monitoring (ISO/TS 21929-1 [13]). Specifically, eco-efficiency indicators are structured to capture resources usage, both in terms of production and consumption and of the consequent environmental impacts (UN ST/ESCAP/2561 [14]).

One of the most comprehensive initiatives for developing indicators for the building sector was the work carried out within the European thematic network "Construction and City Related Sustainability Indicators"- CRISP, providing a database of circa 500 indicators. Later, this network carried out studies concerning the application of these indicators to performance-based buildings. It was concluded that considerable additional work was still required to achieve European indicator systems that could be widely used to support and encourage successful adoption of the performance approach to buildings design and construction (CRISP PeBBu [10]).

The existing sustainable buildings assessment systems offer a number of indicators to be used in different contexts and building life cycle phases (CRISP PeBBu [10]). Recent research projects like SUPERBUILDINGS (Sustainability Performance Assessment and Benchmarking of Buildings) and OPENHOUSE aimed at, among other goals, developing a logical structure for them. While the first focused on research and development of indicators, their reliability, comparability and validity, the latter developed and tested assessment methodologies through case studies (Lutzkendorf et al [11]; Häkkinen, et al. [9]).

## 1.3 Preliminary set of indicators for structural frames selection

Environmental, economic and social performances should be considered in the sustainability assessment of buildings. Indicators used can be organized to allow the inclusion of a broad representation of sustainability aspects while being relevant to the stakeholders' perspectives (UN ST/ESCAP/2561 [14]).

Still, advancement in all three dimensions of the sustainability tripod is not equally balanced. Literature reviewed by Reap et al. [15] and Heijungs et al. [16] has pointed out many unsolved difficulties regarding integration of social aspects to environmental lifecycle assessment, mainly because the former methodologies are still embryonic and lack consensus on crucial impact integration and calculation steps. Furthermore, data regarding functional, environmental, economic and social performance integrated evaluation within a building and its subsystems life cycle are practically inexistent in the Brazilian construction sector, where concrete buildings predominate (Oliveira et al [6]).

Table 1 shows the proposed set of indicators selected using criteria predefined by Oliveira et al [6]. The list comprises functional, environmental and economic metrics. The functional indicators refer to structural and fire safety, adaptability, constructability, maintenance and durability requirements, based upon recommendations of ISO 6240 [17], ISO 6241 [18] and ABNT NBR 15575-1 [19]. The latter does not detail the requirements for environmental performance compliance. Consequently, the environmental indicators were defined according with ISO/TS 21929-1 [13] and ISO 21931-1 [20] and describe resource use intensity and global warming potential. Metrics for other environmental impact categories are currently under study.

Lifecycle cost (LCC) was the indicator chosen to describe the performance in terms of the economy requirement. LCC is obtained through life cycle costing technique, standardized by ISO 15686-5 [21]. The European Commission has also developed an EU-wide LCC methodological framework for buildings and constructed assets as a contribution to sustainable construction (Langdon [22]). The technique estimates the cost of whole buildings, systems and/or building components and materials (ISO 15686-5 [21]), and can assist decision-making in building investment projects or monitor the costs incurred

throughout the lifecycle, including acquisition, development, operation, management, repair, disposal and decommissioning.

## 2. Goals, method and approach

This paper has the general goal to advance on the validation of functional, environmental and economic indicators to allow evaluation of sustainability aspects of concrete structural frames from an integrated, life cycle perspective. Specifically, a case study approach was adopted to investigate *(i)* comparison feasibility of sustainability performance of different concrete building flooring sys-

tems; and *(ii)* representativeness of results achieved for a typical flooring system for all environmental indicators in relation to those obtained for the whole superstructure, analogously to design common practice of examining a building's typical floor as a proxy for the whole superstructure's material consumption.

The set of functional, environmental and economic indicators (Table 1) was calculated for three residential buildings, using either prestressed concrete flat (PCF) slabs or reinforced concrete waffle (RCW) slabs and flat beams exposed to a marine environment, subject to chloride attack. To form a basis for meaningful comparison, quantified functional/technical requirements for a building or a system assembly are expressed

| Table 1 – Functional/technical, environmental and economic indicators proposed for assessment of buildings structural frames (adapted from Oliveira et al (6)) |
|---|
| **Indicators for structural frames/elements** |
| **Functional/technical (associated to performance requirements: structural safety fire safety\*, adaptability, constructability, maintenance, durability\*\*)** | Span over height ratio ($\ell/h$) for each direction considered (for beams and slabs), (m/m) <br> Ultimate strength over applied stress ratio (for columns) - for reinforced or prestressed concrete elements, it is the compressive design stress over the characteristic compressive (cylinder) strength, $f_{ck}/f_c$ (kN/m$^2$ / kN/m$^2$); <br> Column density: Structural floor area over number of columns (m$^2$/ n$^o$), (m$^2$) <br> Beam over slab height ratio, (m/m) <br> Reuse Potential: volume prefabricated with connections for disassembly over total volume ratio (% volume) <br> Concrete volume over structural area ratio (m$^3$/m$^2$) <br> Steel mass over structural area ratio (kg/m$^2$) <br> Fire safety: <br> $h_{solid\ slab\ with\ beams}$ (cm)/12; $h_{flat\ slab}$ (cm)/20 (for P5\*) with $c_1$ =3,0cm for longitudinal reinforcement; and $c_1$=5cm for prestressing tendons. <br> $h_{solid\ slab\ with\ beams}$(cm)/8; $h_{flat\ slab}$(cm)/18 (for P3\*) <br> $b_{rib\ min\ (waffles\ slabs)}$ (cm)/16; $c_1$ =4.5cm; and $h_{flange}$/12; $c_1$=2.0cm (for P5\*) <br> $b_{rib\ min\ (waffles\ slabs)}$ (cm)/10; $c_1$ =2.5cm; and $h_{flange}$/8; $c_1$=1.0cm (for P3\*) <br> $b_{min\ columns\ with\ more\ than\ 1\ face\ exposed}$ (cm)/25 for $h_{total\ height\ of\ the\ building}$ >30m <br> $b_{min\ columns\ with\ more\ than\ 1\ face\ exposed}$ (cm)/19 for 12m<$h_{total\ height\ of\ the\ building}$ <23m |
| **Environmental** <br><br> **(associated to resource intensity and climate change)** | Embodied Carbon equivalent (ECO$_{2e}$) (kgCO$_{2e}$/functional unit (fu)); <br> Embodied Energy (EE) (MJ/fu); <br> Blue Water Footprint (bWF) (m$^3$/fu); <br> Materials Resource Consumption(Mc)(kg/fu): <br> Non Renewable raw material Content (NRc) (kg$_{total\ material}$ – kg$_{recycled}$ – kg$_{reused}$) <br> (kg/ functional unit) |
| **Economic (associated to life cycle monetary flows)** | Life cycle costs, LCC ($/functional unit (fu)) |

\*P3 and P5 correspond respectively to 60min and 120min for the required period of fire resistance for residential, hotel and commercial use; $c_1$ is the distance from steel axis to exposed face. (ABNT NBR 14432 (36)). Based on "Tabular Method" from ABNT NBR 15200 (37).

\*\* According to the ABNT NBR 15575 -1, design life (DL) is a performance criterion to assess the durability requirement. To enable comparison between design alternatives, the required service life (or DL if greater) was selected as a functional equivalent together with the functional requirements and building typology.

in terms of the functional equivalent (SBA [23]; EN 15643-2 [24]). In this study, functional equivalence of different designs shall be expressed in terms of 50-year design life (DL), which is the minimum required service life of a residential building according to the Brazilian performance standard – ABNT NBR 15575-1 [19], building type, exposure conditions and standards for concrete design and construction.

Data for computing the functional indicators were extracted from structural design shop drawings and calculation sheets provided by the responsible structural design practices and the local contractor. SimaPro 7.3 life cycle assessment (LCA) platform supports calculation of the environmental indicators. Service life estimated by Life-365 v.2.1.1 software[1] is used as a functional unit normalizer. LCC calculation by the software was adapted to also follow ISO 15686-5 [21] guidelines.

Life-365 is a shareware computer-modeling program that estimates the time-to-corrosion initiation and life-cycle costs for reinforced concrete exposed to chlorides. Life-365 originally developed under the auspices of a consortium established by the American Concrete Institute (ACI), in the late 90's, as a first step in the development of a more comprehensive model for predicting the life-cycle cost associated with reinforced concrete structures exposed to chlorides. Since launching of version 1.0, in October 2000, it has been widely applied in the USA (Ehlen [25]; Silva et al [26]). This paper uses the version (v. 2.1.1), released in August 2012.

System boundaries established for this study and methodological steps are detailed in the next sections.

## 2.1 System boundaries

### 2.1.1 Building life cycle stage boundaries

Performance of a concrete structural frame shall be described over the building life cycle, which can be broken down into three main stages, in accordance with standard EN 15804 [27]. Phase I takes into account aspects and impacts related to product manufacture and building construction. The in-use stage (Phase II) includes aspects and impacts arising from the maintenance and repair of the structure. Phase III of the life cycle encompasses end of life stage and corresponding destination of disassembled or demolished material.

In this study, the environmental indicators for Phase I do not consider the construction operations and are currently limited to resource intensity and global warming potential resultant form materials usage. Phase III was not considered due to lack of reliable

environmental data for end-of-life alternatives in the Brazilian context. LCC computed data for Phase I, but also disregarded Phase III (end of life stage) due to lack of reliable cost records for design for disassembly and post-use alternatives.

### 2.1.2 Life cycle costs (LCC) boundaries and assumptions

Economical analyses may also be drawn up in early stages of building design *if there is information available on reference data of building related life cycle costs.* Savings may result from the initial or maintenance costs of the structural frame itself, or given by optimization of other building systems. Leveling slab and beam heights, or adopting flat slabs, for instance, brings savings to energy and materials resources consumption due to optimized story heights, reducing sealing/closing walls, and coating, heating and cooling, besides facilitating adaptability. Optimized column layout, for instance, generates better - or even increased number of - parking spaces. Estimation of these and other effects and synergies on life cycle costs is complex and requires detailed data not available for consultation. Moreover, because of the predictive nature of LCC methods, sensitivity analyses are often important in the connection of life cycle economics, but are also drawn out of our scope.

LCC estimation in this paper profited from the use of Life-365 v.2.1.1 software approach (Ehlen [25]), which is built upon a generally accepted LCC framework and based on service life prediction assumptions and output.

### 2.1.3 Environmental life cycle assessment (LCA) boundaries and inventory data sources

Calculation of the environmental indicators was supported by software SimaPro 7.3. The life cycle assessments (LCA) performed followed ISO 14040 [28] methodological guidelines. The defined system boundaries characterize a *cradle to gate* analysis, which disregards transportation and building construction, use and end of life stages.

Data for materials production cycle modeling were taken from national literature or adapted from processes within Ecoinvent or ELCD international databases upon switching into the Brazilian energy mix, since such processes were considered to be similar enough to those carried out in the country. Data obtained from the Worldsteel Association for prestressing steel could not be edited. Table 2 shows the functional unit adopted and data sources used for LCA modeling of the considered production processes.

| Table 2 – Functional unit and inventory data sources for the materials and components considered in the performed life cycle assessments | | |
|---|---|---|
| **Construction materials and components** | **Functional unit** | **Data source** |
| Concrete (fck 30Mpa) [a] | 1 m³ | Silva, 2006 (30) |
| Portland cement (CPIII-32) [a] | 1 ton | Silva, 2006 (30) |
| Steel rebar (reinforcing steel) | 1 ton | ELCD (European life cycle database)* |
| Plywood formwork, Sand, Gravel | 1 m³ | Ecoinvent* |
| Wire Rods (prestressing steel) | 1 ton | WorldSteel Association |

[a] Concrete mix with cement type CPIII-32 (66% of ggbs as clinker replacement)
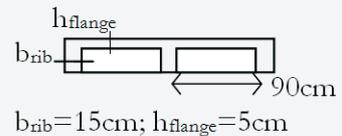*Adapted to Brazilian energy mix
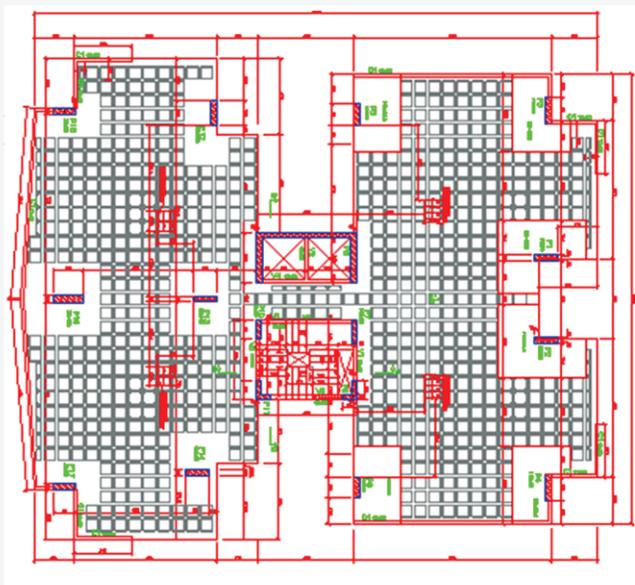
**Case study 1 - Building A**

Flooring system:

27.5 cm-thick reinforced concrete waffle slabs with flat beams, fck 30 MPa

$b_{rib}=15cm$; $h_{flange}=5cm$

Number of floors: 6
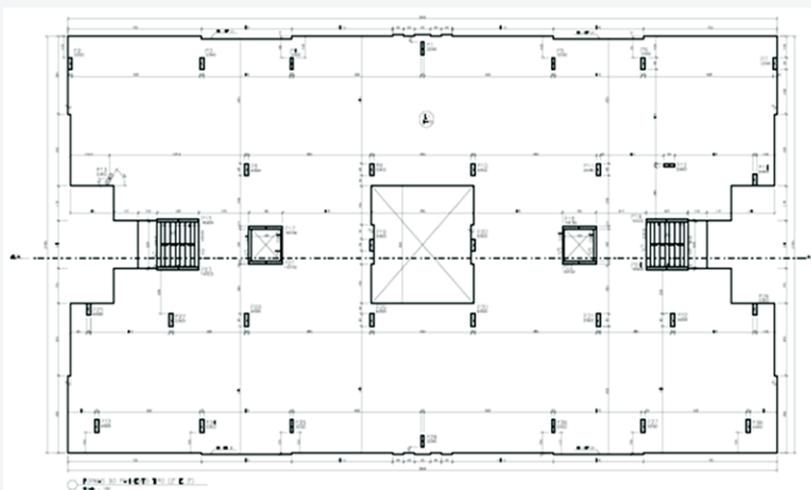
Total structural area: 5470 m²
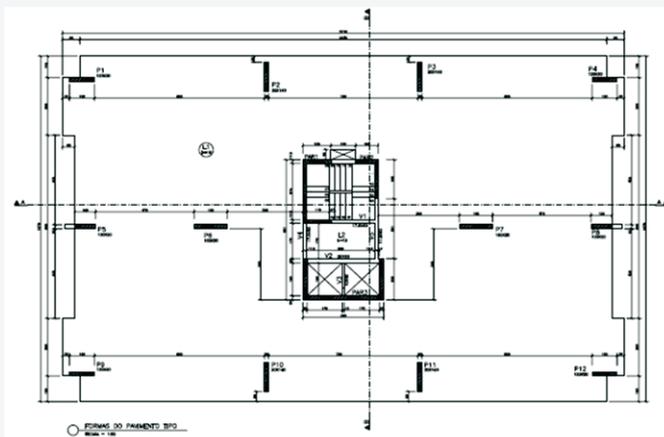
**Case study 2 - Building B**

Flooring system:

18 cm-thick flat prestressed slabs (no beams), fck 30 MPa

Number of floors: 15

Total structural area: 7105 m²

**Case study 3 - Building C**

Flooring system:

18 cm-thick flat prestressed slabs (no beams), fck 30 MPa

Number of floors: 6

Total structural area: 4640 m²

Modeling of CP III-32 blended cement production has not considered any impact allocation criterion between steel and ground granulated blast furnace slag (ggbs). This assumption reflects the current practice of considering ggbs as a waste, with no environmental load, and is also aligned with ISO 14040 [28] recommendation to avoid allocation whenever unessential. Allocation is a widely recognized and challenging methodological problem in LCA for its potential significant impact on the results, but was not imperative for this study's purpose.

### 2.2 Case studies description

The indicators are calculated for three case studies comprising low-and medium-rise concrete-framed residential buildings, using either reinforced concrete waffle (RCW) slabs and flat beams (Case study 1) or prestressed concrete flat (PCF) slabs (Case studies 2 and 3). Two PCF cases studies with 6 and 15 stories are analyzed to check if similarity between environmental indicators trends for a typical flooring system and corresponding whole superstructure would be sensible to a building's number of floors.

All of them are located in the Brazilian city of Vitoria – ES, configuring a marine environment subject to chloride attack (Class III of ABNT NBR 6118 [29]). Case study 1 has a total built area of 5,829.19 $m^2$ (6 floors, 24 apartments); Case study 2 has 8,841.37 $m^2$ (15 floors, 48 apartments) and Case study 3 has 4,943.31 $m^2$ distributed in 6 floors (32 apartments). Figure 1 summarizes the case studies' description.

All case studies specified a concrete with characteristic compressive strength of cylindrical specimens (fck) of 30 MPa. As no recorded information for the original mixes was available, the calculations in this paper are based on mixes lab-designed by previous research for the same region of study (Vitória - ES), where Portland cement CP III-32 is commercially dominant (Silva et al. [30]). Mix proportions (1: 2.5: 2.3: 0.5 of cement:

sand: aggregate: water, in mass) and cement consumption (380 kg/m³) were estimated from design curves pre-charted in laboratory for CP III-32, upon design strength (fcd) input. For this blended cement, ABNT NBR 5735 [31] accepts clinker substitution for up to 70% ground granulated blast furnace slag (ggbs). Substitution is however normally limited to 58%, considered the commercial viability threshold for joint grinding of clinker and ggbs. In the particular case of Silva et al [30], clinker substitution for 66% of ggbs represents a specific commercial situation, obtained by separate grinding. Quantitative design data collected for calculation of indicators are shown in Table 3.

### 2.3 Service life prediction modeling and assumptions

Service life (SL) is defined as *period of time after installation during which a building or an assembled system (part of works) meets or exceeds the technical requirements and functional requirements* (EN 15643-2 [24]). SL may be determined using quantitative service life prediction models for a particular element in a given environment. For chloride-driven corrosion in marine environments, many of these models adopt the widely acknowledged two-stage SL approach suggested by Tuutti [32] in which the deterioration is split into initiation and propagation periods. That is the case for software Life-365 v.2.1.1 (Ehlen [25]), used in this paper.

The initiation period, $t_i$, represents the time taken for the critical threshold chloride concentration, $C_t$, to reach the depth of cover, $c_{min}$, and initiate corrosion of the embedded steel. The length of this period is a function of concrete quality, cover depth, exposure conditions (including the level of chloride at the surface and the temperature of the environment) and $C_t$ required to initiate corrosion. No damage (due to chlorides or corrosion) is assumed to occur during this period (Ehlen [25]).

Life-365 v.2.1.1 adopts a simple approach to predicting $t_i$ and assumes that ionic diffusion is the sole mechanism of chloride trans-

### Table 3 – Design data collected for indicators' calculation

| Design data | Design data | | |
| --- | --- | --- | --- |
| | CS1 RCW | CS2 PCF | CS3 PCF |
| Concrete volume, (m³) | 121.1 | 80.9 | 131.9 |
| Reinforcing steel CA 50, (kg) | 10657 | 2927 | 4465 |
| Prestressing steel-CP 190 (unbounded tendons), (kg) | 0 | 1566 | 2100 |
| Cast iron anchorages (unit = plate + edge anchor) 0,5kg/unit, (unit) | 0 | 112 | 136 |
| Plywood formwork area [a] (17mm-thick), (m²) | 197.5 | 92.6 | 185.8 |
| Structural area of the typical floor, (m²) | 784.83 | 458.40 | 773.20 |
| Number of columns at typical floor, (unit) | 44 | 15 | 39 |
| Slab span - $\ell$, (cm) | 6.8 | 7.3 | 6.0 |
| Slab thickness - $h_l$, (cm) | 27.5 [b] | 18.0 | 18.0 |
| Beam height - $h_v$, (cm) | 27.5 | 18.0 [c] | 18.0 [c] |
| Internal column width - $h_{col}$, (cm) | 20 | 20 | 20 |

[a] considering maximum of five formwork reuse cycles; [b] waffle slab concrete volume equivalent to a 14.7cm-thick solid slab
[c] for the flooring systems with no beams, beam height is taken as slab height
PCF = prestressed concrete flat slab; RCW = reinforced concrete waffle slab and flat beams

port and that concrete is completely saturated, in order to solve Fick's second law of diffusion, given by the differential equation:

$$\frac{dC}{dt} = D \cdot \frac{d^2C}{dx^2} \tag{1}$$

where,

C = the chloride content,
D = the apparent diffusion coefficient,
x = the depth from the exposed surface, and
t = time.

The chloride diffusion coefficient is a function of both time and temperature, and Life-365 uses Equation 2 to account for time-dependent changes in diffusion:

$$D(t) = D_{ref} \cdot \left(\frac{t_{ref}}{t}\right)^m \tag{2}$$

where,

D(t) = diffusion coefficient at time t,
Dref = diffusion coefficient at time $t_{ref}$ (= 28 days in Life-365), and
m = diffusion decay index, a constant.

Life-365 selects values for $D_{ref}$ and $m$ based on mixture design input (i.e., water- cementitious material ratio, w/cm, and the type and proportion of cementitious materials). Equation 2 is assumed to be only valid up to 25 years, beyond which *D(t)* stays constant at the *D(25 yrs)* value.

Also, Life-365 uses Equation 3 to account for temperature-dependent changes in diffusion:

$$D(T) = D_{ref} \cdot \exp\left(\frac{U}{R} \cdot \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right) \tag{3}$$

where

D(T) = diffusion coefficient at time t and temperature T,
$D_{ref}$ = diffusion coefficient at time tref and temperature $T_{ref}$,
U = activation energy of the diffusion process (35000 J/mol),
R = gas constant, and
T = absolute temperature.

The solution for time to initiation of corrosion is carried out using a finite difference implementation of Equation 1 where the value of $D$ is modified at every time step using Equation 2 and Equation 3. Implicit in the model are the following assumptions: the material under consideration is homogeneous (e.g. no surface effects); constant superficial chloride concentration; the properties of the elements are constant during each time step, calculated at the start of each time step; and the diffusion constant is uniform over the depth of the element (Ehlen [25]). The required input parameters for service life prediction are: structure type and dimensions; temperature and chloride exposure conditions; details of each protection strategy scenario, such as w/cm ratio, type and quantity of mineral admixtures and corrosion inhibitors, type of steel and coatings, and type and properties of membranes or sealers (Ehlen [25]).

Though the default propagation period, *tp*, is fixed at 6 years,

based on studies from Weyers, [33]; Weyers et al. [34] - or at 20 years, if epoxy-coated steel is used - it can be changed to reflect local expertise (Ehlen [25]) and redefine time to first repair *(tr)*, which marks the end of ESL *from the perspective of the adopted chloride attack model*. In our case, the *time for first repair* triggers the maintenance program defined to allow all case studies to reach a minimum of 50-year DL required by ABNT NBR 15575-1 [19] and ensure functional equivalence for both LCA and LCC calculations. The default 10-year interval between repairs was considered to reasonably represent current practice.

## 2.4 Calculation of the environmental indicators

Life cycle inventories of LCAs provide data concerning resources consumed as well as emissions and waste produced throughout all phases of the evaluated life cycle, supporting calculation of the environmental indicators per one functional unit defined for each material. The embodied energy (EE - MJ/fu) calculation sums the listed amounts of primary energy consumed from raw material extraction to manufacturing. Analogously, the embodied $CO_{2e}$ ($ECO_{2e}$ – kg $CO_2$/fu) calculation computes all greenhouse gases emissions listed in the inventory. The blue water footprint (bWF - m³/fu) calculation totalizes the water – obtained from ground and surface water sources - consumed during the extraction and production (Hoekstra et al [35]). Finally, the abiotic raw material content (NRc - kg/fu) calculation sums the consumption of all non-renewable mineral resources. Materials Resource Consumption (Mc) is given in terms of the total mass of steel, concrete and plywood formwork used per functional unit (Table 1).

A 10 % extra volume of material was assumed for each predicted flooring system repair event and added to the overall material consumption of the respective floor. These values per functional unit were then multiplied by consumption of each material, including the material added by predicted repair events. Foundations were disregarded to isolate the effects of soil's carrying capacity on sizing, and consequently on material consumption. These indicators were then normalized by the structural area (m² SA) and calculated for one typical floor and for the total superstructure of each case study.

## 2.5 Calculation of the economic indicator

LCC estimation by software Life-365 v.2.1.1 considers only concrete and rebar data. Thus, an input data adaptation was required to include plywood formwork and prestressing steel costs and labor. Therefore, for one typical floor, the total cost of plywood formwork including labor was divided by the concrete volume, and then added to the concrete cost with labor per cubic meter. Similarly, cost of steel input represents the weighted average between reinforcing and prestressing steel costs per kg, including anchors and labor. Workmanship costs for maintenance were calculated from reference costs tables (February 2013) published by LABOR, the Federal University of Espírito Santo's construction costs estimates laboratory [36].

Four economic parameters shall be set for LCC calculation using software Life-365 v.2.1.1: reference period, reference year, annual inflation rate and real discount rate. The 50-year DL required by ABNT NBR 15575-1 [19] was considered as the *reference period*, being 2013 set as the *reference year*.

LCC was given by the sum of the initial construction costs and the discounted future repair costs, including material and labor, over the design life of each flooring system. For the reasons previously mentioned, end

of life costs were not included in the current calculation. Maintenance cost estimation considered the same schedule and assumptions established for LCAs: 10% extra volume of material and corresponding labor cost per repair event, carried out at 10-year intervals, beginning at the time for first repair. Future material and labor costs are calculated on a present worth basis using the inflation rate, $i$, and the real discount rate, $r$. The present worth, $PW$, of a future cost $c$ in year $t$ is given by Equation 4.

$$PW = c \left(\frac{1+i}{1+r}\right)^t \tag{4}$$

*Annual inflation rate* of 6.59% and *real discount rate* of 7.5% were adopted. These figures respectively represented the Price index to consumer rate (IPCA), defined by the Brazilian Institute of Applied Economic Research (IPEA), and the special system of liquidation and custody rate (SELIC) established by the Brazilian Monetary Policy Committee in April 2013.

## 3.   Results and discussions

Table 4 shows all indicators results for the studied cases. The highlighted values are the best result achieved for each indicator. Concerning the functional performance, the PCF slabs presented

| Table 4 − Results of functional/technical, environmental (resource use) and economic indicators | | | | | |
|---|---|---|---|---|---|
| Performance requirements | | Indicators | One typical floor | | |
| | | | Case 1 RCW | Case 2 PCF | Case 3 PCF |
| Structural safety | | Span over height ratio ($\ell/h$) (m/m) | 24.7 | **40.3** | 33.3 |
| | | Ultimate strength over applied stress ratio ($fck/fc$) ($kN/m^2/kN/m^2$) | N/A | N/A | N/A |
| | | Concrete volume over structural area ratio ($m^3/m^2$) | **0.15** | 0.18 | 0.17 |
| | | Steel mass over structural area ratio ($kg/m^2$) | 13.58 | 9.80 | **8.49** |
| Fire safety | | $h_{flat\ slab}$ (cm)/20 for CS2; $h_{flat\ slab}$ (cm)/18 for CS1,CS3 | - | 0.9 | **1.0** |
| | | $b_{rib\ min\ (waffles\ slabs)}$ (cm)/10 with c1 =2.5cm; and $h_{flange}$/8 with $c_1$=1.0cm | 1.5; 0.63 | - | - |
| | | $b_{min\ columns\ with\ more\ than\ 1\ face\ exposed}$ (cm)/25 (≥1) CS2 | 1.05 | 0.8 | 1.05 |
| | | $b_{min\ columns\ with\ more\ than\ 1\ face\ exposed}$ (cm)/19 (≥1) CS1,3 | **1.05** | 0.8 | **1.05** |
| Constructability | Maintenance Adaptability | Reuse potential (% volume) | 0 | 0 | 0 |
| | | Column density ($m^2$/nr columns) | 17.8 | **30.6** | 19.8 |
| | | Beam over slab height ratio, (m/m) | **1** | **1** | **1** |
| | Durability | Estimated service life (yrs) = time to first repair (estimated for $c_{min}$=2.0cm; $D_{28}$=1,38E$^{-11}$; m=0.58; Ct=0.05) | **11.7** | 11.2 | 11.2 |
| Environmental adequacy / Impact categories considered | Climate change | Embodied Carbon Equivalent (ECO$_{2e}$) ($kgCO_{2e}/m^2$ SA) — typical floor | 51.74 | 41.44 | **38.76** |
| | | superstructure | 61.20 | 76.09 | **59.45** |
| | Intensity of resources use | Embodied Energy (EE) ($MJ/m^2$ SA) — typical floor | 440.02 | **324.35** | 332.75 |
| | | superstructure | **766.01** | 783.13 | 797.97 |
| | | Blue Water Footprint (bWF) ($m^3/m^2$ SA) — typical floor | **1.24** | 1.55 | 1.44 |
| | | superstructure | **1.38** | 2.19 | 1.88 |
| | | Material resource consumption (Mc) ($kg/m^2$ SA) — typical floor | **541.05** | 609.76 | 588.62 |
| | | superstructure | **548.76** | 837.77 | 721.40 |
| | | Abiotic (noon-renewable) raw material content (NRc) ($kg/m^2$ SA) — typical floor | **475.34** | 536.91 | 517.98 |
| | | superstructure | **475.76** | 731.41 | 626.25 |
| Economy | | LCC ($US\$/m^2$ SA) | 341.55 | 311.89 | **300.35** |

SA = structural area

| Case study (CS) | Typical floor slab | Estimated Service Life (ESL)= time to first repair (years) | Life cycle cost [a] (LCC) US$/m² structural floor area | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Construction costs | | | | | Repair cost [c] | Total life cycle cost |
| | | | Plywood formwork [b] | Concrete | Rebar | Prestressing steel | Total construction costs | | |
| 1 | RCW | 11.7 | 13.34 | 28.24 | 45.90 | 0.00 | 87.48 | 254,03 | 341,55 |
| 2 | PCF | 11.2 | 10.71 | 32.30 | 21.58 | 11.10 | 75.61 | 236,24 | 311,89 |
| 3 | PCF | 11.2 | 12.96 | 31.22 | 19.52 | 8.83 | 72.53 | 227,94 | 300,35 |

**Table 5 – Service life estimated by Life-365 v.2.1.1, ESL (time to first repair) and life cycle cost of a typical floor of each case study**

[a] Sum of the initial cost (construction) and costs of repair events, discounted to present value. Base year 2013.
[b] considering plywood formwork reuse of five times maximum.
[c] values corresponding to four events of repairs, discounted to present value.

the best results for *span over slab ratio* and *column density indicators* (CS2) and *steel over structural area ratio* and *fire safety indicators* (CS3), while the RCW slab of CS1 performed best concerning *concrete volume over structural area ratio*.

The *Reuse Potential indicator* was nil for all cases as the slabs were cast *in situ* and not designed for disassembly. CS1 (reinforced concrete waffle slab with flat beams) has better end-of-life performance, due to smaller spans and existence of beams, which make demolition easier and safer, resulting in lower demolition costs than the PCF slabs used in CS2 and CS3. Furthermore, reinforcing steel has higher recycling market value than prestressing steel. Notwithstanding, the flooring system with no beams and longer spans (CS2) provides increased adaptability.

Regarding the fire safety requirement, the results for the proposed indicators shall be equal or greater than 1, as occurred for CS3. This means that case study 3 is the only one to comply with fire safety requirements of both ABNT 14432 [37] and ABNT NBR 15200 [38].

Under the conditions studied, designing reinforced concrete structures for a marine environment according to ABNT NBR 6118 [29] (Class III of environmental exposure) *per se* does not ensure compliance with ABNT NBR 15575-1 [19] durability requirement and design life criteria. The results of service life prediction for the studied conditions (Table 5) confirm that the repair schedule selected allowed the 50-year minimum DL required by ABNT NBR 15575-1 [19].

According to ABNT NBR 6118 [29], the nominal cover ($c_{nom}$) defines the minimum concrete cover ($c_{min}$) plus a tolerance of execution ($\Delta c$). For usual situations, it is recommended $c_{nom}$ of at least 35 mm and 45 mm for reinforced and prestressed concrete slabs, respectively, in a marine environment (Class III) and 10mm $\Delta c$, which means $c_{min}$ of 25mm and 35mm. The case studies reflect current practice of structural design, which adopts in a marine environment, for both slab types, $c_{min}$ of 20 mm and $\Delta c$ equal to 5 mm, which is consistent with a strict execution control.

Regarding RCW slabs, this attitude is supported by the standard itself, which allows consideration of a microclimate with a milder class of aggressiveness (one level up) for indoor dry environments or concrete coated with mortar and paint, and assumes strict control ($\Delta c$ = 5 mm) provided it is stated in the design drawings (Table 6.1, ABNT NBR 6118 [29]). Thus, the nominal slab concrete cover, $c_{nom}$, decreases from 35 mm (Class III) to 25 mm (Class II) and, considered the additional reduction of 5 mm, reaches the 20 mm minimum concrete cover adopted in the case studies. For these buildings, located at a coastal area, this cover thickness proved to be clearly incompatible with the chloride exposure condition and decisively lowered the estimated SLs (Table 5).

Table 6 shows that, for an assumed $c_{min}$ of 30 mm for RCW (CS1) and of 40 mm for PCF (CS2 and CS3), at ABNT NBR 6118 [29] Class III of exposure, the ESLs calculated by Life-365 v.2.1.1 do not reach the 50-year minimum DL. If a corrosion inhibitor (calcium

**Table 6 – Diffusion properties and corresponding service life estimated (ESL) = time to first repair by Life-365 v. 2.1.1 software for the case studies' slabs, considering the minimum concrete cover prescribed by ABNT NBR 6118:2007 (29)**

| D28 m²/s | m | $c_{min}$ mm | Protection strategy for concrete slabs | Ct %wt. conc. | ESL (yrs) | | |
|---|---|---|---|---|---|---|---|
| | | | | | CS1 | CS2 | CS3 |
| 1,38 E-11 | 0.58 | 30 (RC) 40 (PC) (ABNT NBR 6118) | no corrosion inhibitor | 0.05 | 15.8 | 21.5 | 21.5 |
| | | | 17.5L/m³ Ca(NO₂)₂ | 0.28 | 56.8 | 94.2 | 94.2 |

$c_{min}$ prescribed for environmental exposure ABNT NBR 6118 Class III

nitrite - $Ca(NO_2)_2$ - in the proportion of 17.5 l/m$^3$) is added, the estimated SL is further increased and finally exceeds the required service life.

Despite acknowledging Life-365 v.2.1.1 simplified assumptions, accounting for multimechanistic transport in partially saturated concrete requires detailed knowledge of site specific conditions and a wide range of material properties that are not usually available to the engineer at the design stage.

At typical floor level, Figure 2 shows that CS1 (RCW) achieved the best results for bWF, NRc and Mc, but was outperformed by PCF CS2 and CS3 regarding EE and ECO$_{2e}$, respectively. Results for the whole superstructure showed a similar trend, except for EE, whose best result was achieved by RCW CS1.

The Life-365 ESLs for the three case studies were similar because, despite different slab thickness, they had identical characteristic strength; concrete mix composition, minimum concrete cover, chloride exposure conditions (800 m from the shore, as considered by Life-365), and average monthly temperature, taken from Vitoria airport's meteorological station.

Table 5 also presents values of LCC for the typical floors of the case studies, showing the best results for CS2. Overall building LCC estimation would address the savings provided by (i) the lowest column density of CS2 (Table 4) concerning parking spaces and typical floors adaptability, (ii) the reduction from a 27.5cm thick RCW slab (CS1) to 18cm-thick PCF slabs of CS2 and CS3 on envelope plaster and coating consumption and costs, and (iii) the smallest dead weight of CS1 RCW slab (equivalent to a 14.7cm-thick flat slab) contribution to whole superstructure sizing and foundations. Monetary figures and flows related to such strategies and benefits are usually not readily available at structural design practices, and therefore were not provided for inclusion in the case studies. Implementation of continuous value engineering techniques during design would enable reasonably accurate estimation and allow the recommended integrative approach.

## 4. Conclusions

This case study application confirmed the feasibility of calculating the proposed lifecycle-based indicators to assess important sustainability aspects of buildings' structural frames in concrete. Specific conclusion could be drawn from the investigation carried out:

a) **Estimated SL and standards ABNT NBR 6118 and NBR 15575-1**

■ Structural design for marine environment (Class III), according to ABNT NBR 6118 [29], does not ensure compliance with ABNT NBR 15575-1 [19].

■ Proposing a repair schedule, an increase of concrete cover and the use of corrosion inhibitors were the alternatives for compliance checked using Life-365 v.2.1.1 software. Specification of the minimum concrete cover for Class III, waiving the reduction to Class II currently accepted by ABNT NBR 6118, combined to the use of corrosion inhibitor allowed reaching compliance to minimum design life determined by NBR 15575-1 performance code.

■ Although the service life prediction by Life-365 software can be simplified and conservative, it takes into account the presence of admixtures to the concrete. Thus, the results of the performed simulations suggest a potential need for revision regarding the concrete cover specified for Class III applications (table 6.1 of ABNT NBR 6118).



**Figure 2 – Environmental indicators (ECO$_{2e}$, bWF, EE, NRc and Mc) normalized per unit of structural area, calculated for the typical floor and whole superstructure of the case studies, assuming Implementation of measures to achieve a 50-year DL, as estimated by Life-365 v.2.1.1 software**
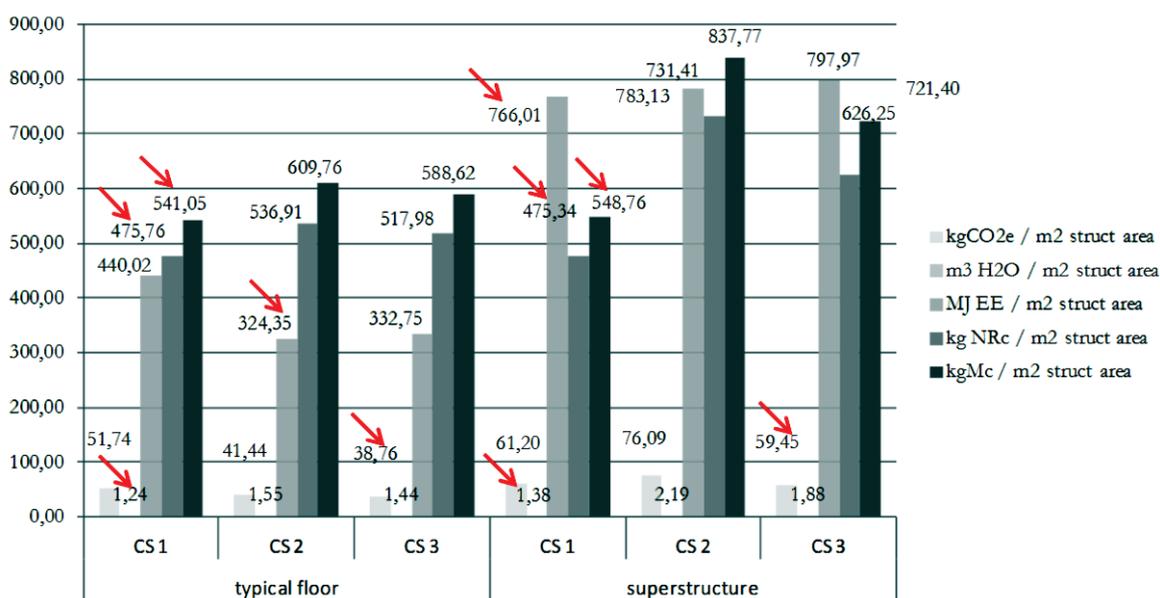
**b) Functional/technical, economic and environmental indicators**

■ PCF slabs showed best results for most functional/technical and for economic indicators but were outperformed by RCW slabs' environmental results.

■ When designing structural frames more attention should be paid to the minimum required concrete cover of PCF slabs for fire safety.

■ LCC for CS1 was 14% greater than for CS3, while the differences between CS2 and CS3 (~4%) were negligible.

■ Except for embodied energy, all environmental indicators showed the same trend for both typical floor and whole superstructure. The buildings' number of stories did not affect the observed similarity.

■ NRc and bWF results for CS1 were lower than those for CS3 and CS2 at superstructure scale.

■ For EE the differences among results for the three case studies were negligible (~4%) at superstructure scale, but, at typical floor level, CS1 results were 32% and 35% higher than CS3 and CS2.

■ For $ECO_{2e}$, CS1 results at typical floor level were 33% and 25% greater than CS3 and CS2, respectively, while, at the superstructure scale, the differences among CS1 and CS3, with 6 stories, were negligible (~3%) and CS1 (15-story) results were 20% lower than those for CS2.

**c) Final summary**

It is expected that this set evolve to a framework of functional, environmental and economic indicators as a tool to support design decision-making regarding important sustainability aspects in concrete structural frames selection.

Due to the limited number of case studies, these findings are promising but still exploratory. There are twenty-eight case studies currently under analysis. If confirmed for this larger sample, this measure will provide a significant reduction of time and effort in collecting data to calculate the indicators. Next research steps include enlargement of case study library and application of analytic hierarchy process to define indicators relative importance or weighting scenarios to streamline identification of a top performing solution even if the metrics show contrasting trends.

# 5. Acknowledgements

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