Exploring life-cycle-based indicators for integrated sustainability assessment of building structural frames in concrete

Flávia Ruschi M. de Oliveira[1], Maristela G. da Silva[2], Vanessa Gomes[3]

Abstract

Methodologies for indicators selection and benchmarking are paramount to allow quantification of limits and presentation of strategies for achieving sustainability in the construction industry. Life cycle-based studies have consistently shown structural frames and envelopes as major contributors to buildings environmental loads. Despite that, structural frames have not gained enough space in sustainable buildings assessment systems. Given the difficulty to insert life-cycle assessment (LCA) in daily routine of structural design practices, this paper presents a set of LCA- and LCC-based indicators that integrates functional, environmental and economic performance requirements. The goal is to allow proper design decision-making support and a broader, life-cycle, sustainability evaluation of concrete structural frames. Based on a case study approach, the analysis focuses on different concrete building flooring systems. Life-365 software was used to predict service life and estimate LCC for different concrete building typologies. Cradle-to-gate LCAs were performed for reinforcing and prestressing steel, plywood formwork and the concrete mixes. For the conditions studied, prestressed flat slabs showed better functional and economic results than reinforced concrete waffle slabs, which, however, presented the best environmental performance. Results also confirmed the validity to proceed with the analysis of a typical storey *in lieu* of the whole building structure for different residential building typologies, as well as the need to further explore cost and environmentally effective strategies to increase concrete structures service life in marine and industrial environments for compliance with the Brazilian standard ABNT NBR 15575:2012. It is expected that this set of indicators, refined by other case studies, will evolve to a multidimensional framework to support sustainability-oriented structural design decision-making.

Keywords: indicators, structural frame, LCA, LCC, flooring systems.

1. Introduction

Research initiatives for new generations of sustainable buildings assessments state that buildings sustainability level should always be described using indicators. The selection and

[1] Adjunct Professor, Department of Civil Engineering, Federal University of Espírito Santo, Brazil, flaviaruschi@gmail.com
[2] Associate Professor, Department of Civil Engineering, Federal University of Espírito Santo, Brazil, margomes.silva@gmail.com
[3] Associate Professor, Department of Architecture and Construction, University of Campinas, Brazil, vangomes@fec.unicamp.br

justification of indicators should be based on clear understanding about the issues of concern and the relevance of building sector to these issues (SUPERBUILDINGS, NEWSLETTER-2, 2011, CRISP PeBBu, 2005, LUETZKENDORF et al, 2011). 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, 2003), 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 21929-1:2006).

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, 2010).

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, 2005).

The existing sustainable buildings assessment systems offer a number of indicators to be used in different contexts and building life cycle phases (CRISP PeBBu, 2005). Research projects like SUPERBUILDINGS (Sustainability Performance Assessment and Benchmarking of Buildings) and OPENHOUSE currently aim to, among other goals, develop a logical structure for them. While the first focuses on research and development of indicators, their reliability, comparability and validity, the latter develops and tests assessment methodologies through case studies (SUPERBUILDINGS, NEWSLETTER-2, 2011).

The literature review pointed out difficulties on integrating social aspects to environmental LCAs (REAP, 2008), such as *(i)* the lack of consensus on how to integrate and calculate social impacts of products, since social impact methodologies are still in their infancy; and *(ii)* the fact that most impacts on people are independent of the physical processes of manufacturing, increasing complexity on the product-impact relationship.

Another important issue concerning sustainability is durability (LORENZ, 2008), as it decisively influences the service life of buildings and the amount of resources required for maintenance activities. Service life of the structural frame ultimately defines the lifespan and consequently the maintenance intensity of a building. It therefore influences not only the environmental performance of buildings, but its social and economic performances as well.

Life cycle-based studies have shown the structural frame and envelope as major contributors to material environmental loads of a building (DOBBELSTEEN et al, 2005, DOBBELSTEEN et al, 2007, HAAPIO, VIITANIEMI, 2008, KELLENBERGER, ALTHAUS, 2009, MOON, 2009). However, service life, durability, and role played by structural frames have not gained enough attention in sustainable buildings assessment systems, except perhaps for HQE/AQUA and CASBEE, which include service life extension of the structural frame among their encouraged sustainability strategies.

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, 2008).

A building's design life, as well as the service life of building elements, also defines its environmental performance in terms of material use, once sustainability is given by the ability to fulfil 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, 2011).

Considering *(i)* that service life of the structural system ultimately defines the lifespan of a building, *(ii)* that service life is also determinant of the efficiency of resource use for a given function, *(iii)* the role of structural systems in environmental terms, mentioned by studies in other contexts, and *(iv)* the complete absence of data in this regard in Brazil, this work is dedicated to the study of alternative structural systems typically used in Brazilian residential concrete buildings typology. Other relevant building systems as well as the relation with the other parts of the building and the impacts on the technological system as a whole are being targeted by parallel research and are therefore beyond the scope of the present paper.

Life cycle environmental and costs consideration, service life prediction models and functional requirements should be properly balanced and used to support design decision-making. Eco-efficiency indicators are structured to capture resources usage – both in terms of production and consumption – and the consequent environmental impacts (UN ST/ESCAP/2561, 2010).This paper aims at proposing a set of LCA- and LCC-based eco-efficiency indicators to evaluate sustainability aspects of concrete structural frames from a life cycle perspective. A case study approach was adopted to investigate its feasibility to compare sustainability performance of different concrete building flooring systems.

2. Method and approach

The present study was developed in the following steps: *i)* literature review, covering the concept and methodology for developing sustainability and eco-efficiency indicators for the building sector, and the building performance requirements recommended by the Brazilian performance standard (ABNT NBR 15575:2012) as well as ISO 6240:1980 and ISO 6241:1984; *ii)* proposition of a set of indicators for the selection of structural frames, based on functional, environmental and economic performance requirements; *iii)* application of these indicators for election from a choice of structural flooring systems at the design stage. The final sessions of the paper are dedicated to results presentation and discussion.

2.1 Preliminary set of indicators for structural frames selection

The functional indicators proposed in this paper refer to stability, fire safety and safety in use, flexibility and durability requirements, based on ISO 6240:1980, ISO 6241:1984 and ABNT NBR 15575:2012, the Brazilian standard for buildings performance. The set of environmental performance indicators is based on ISO/TS 21929-1:2006 and mainly associated to resource management. It measures environmental performance of structural frames in accordance with ISO 21931-1:2010 methodological guidelines. Economic indicators describe monetary flows connected to the building. The economic indicators suggested shall provide a balance between its long-and short-term economic aspects. The indicators considered in this study were life cycle costs, payback period and local economy support. Table 1 shows the proposed set of indicators, filtered by predefined criteria (OLIVEIRA et al, 2011).

Table 1 – Set of functional, environmental and economic indicators proposed for selection of buildings structural frames

Indicators for structural frames / elements	
Functional (associated to performance requirements: safety, adaptability / flexibility, constructability)	*Span over height ratio* (ℓ/d) for each direction considered (for beams and slabs), [m/m] *Applied stress over ultimate strength ratio* (for columns) - for reinforced or prestressed concrete elements, it is the compressive design stress over the characteristic compressive (cylinder) strength, fc / fck [kN/m^2 / kN/m^2]; *Column density:* gross floor area over number of columns (m^2/ n^o), [m^2] *Beam over slab height ratio*, [m/m] *Reuse Potential:* % prefabricated with connections for disassembly [% volume]
Environmental (associated to resource management)	*Carbon Footprint* (CF) [$kgCO_{2\text{-}eq}$/functional unit]; *Embodied Energy* (EE) [MJ/ton]; *Blue Water Footprint* (bWF) (surface and groundwater used, except water for turbine use) [m^3/ functional unit]; *Materials resource consumption* (Mc) [kg/ functional unit]: Steel consumption; Concrete consumption; Plywood formwork consumption; and Structural system consumption (steel + concrete+ plywood formwork). *Abiotic Depletion Potential* (ADP) [($kg_{\text{total material}}$ – kg_{recycled} – kg_{reused}) / functional unit]
Economic (associated to life cycle monetary flows)	*Life cycle costs, LCC* [$/functional unit]; Initial costs of design and construction = investment cost [$/functional unit]; Maintenance costs [$/functional unit]; Recycling and reuse costs [$/functional unit]; Demolition costs [$/functional unit]; Final disposal costs [$/functional unit]; *Payback period,* investment cost ($) over annual economy provided ($) [years] *Local economy support*, local materials over total materials cost (percentage of material and products extracted or fabricated locally – within a 300 km - radius) [% cost].

2.2 Case studies description

Three case studies on structural flooring systems, used in different residential concrete building typologies in the Brazilian coastal area are presented. They comprise low-and medium-rise concrete-framed residential buildings. Case study 1 has a total built area of 5,829.19 m^2, in 6 floors (24 apartments), with a 27.5cm-thick flooring system comprising reinforced concrete waffle slabs and beams. Case study 2 (8,841.37m^2 in 15 floors; 48 apartments) and Case study 3 (4,943.31m^2 in 6 floors; 32 apartments) have 18cm-thick prestressed concrete flat slabs flooring systems. The structural material/components' usage was quantified for all three buildings from cost estimates spread sheets and structural design drawings provided by the local construction company. For each case study, environmental indicators were calculated for two situations: one typical floor and the total superstructure. Foundations were disregarded to isolate the effects of soil's carrying capacity on sizing, and consequently on material consumption. These case studies were selected to allow *(i)* calculation of functional indicators, some of which specific for structural elements/components; *(ii)* investigation of the representativeness of a typical floor structure on the whole superstructure sustainability performance, for environmental aspects, as occurs in traditional structural design for these typologies; and *(iii)* indicators validation.

2.3 Calculation of multidimensional indicators

Data for computing the functional indicators was extracted from structural design shop drawings and calculation sheets provided by the responsible structural design practices.

Cradle to gate LCA studies for calculation of the environmental indicators were supported by software SimaPro 7.3 and performed following ISO 14040:1997 methodological guidelines. Construction use of materials and disposal stages were therefore disregarded. No impact allocation criterion between steel and ground granulated blast furnace slag (ggbs) was applied. Data for materials/components production cycle modelling were taken from national literature or adapted from processes within SimaPro built-in Ecoinvent database upon switching into the Brazilian energy mix. Table 2 **- Functional unit and inventory data source for materials/components studied**

Construction materials and components	Functional unit	Data source
Concrete (fck 30MPa) [a]	1 m^3	Silva, 2006
Portland cement (CPIII-32) [a]	1 ton	Silva, 2006
Steel rebar (reinforcing steel)	1 ton	ELCD (European life cycle database)
Plywood formwork, Sand, Gravel	1 m^3	Ecoinvent
Wire Rods (prestressing steel)	1 ton	WorldSteel Association
[a] Concrete mix with cement type CPIII-32 (66% of ggbs as clinker replacement in cement)		

Service life is defined as the period between construction and the time to the first repair (tr), which may be determined using quantitative service life models for a particular element in a given environment. In this study, software Life-365 v.2.1 supported the prediction of life-cycle costs of reinforced concrete structures exposed to chlorides (Life-365 Manual, 2012). Parameters considered are structure type and dimensions; temperature, chloride exposure conditions; concrete mix characteristics, such as water-cementitious materials ratio (w/cm), and replacement of cement (%) by slag, Class F fly ash, or silica fume (SCMs); prestressing steel and steel rebar type, and *steel over concrete cross sectional area ratio* (%).

To enable comparison and level the life span to reach 40 years design life, LCA-based indicators considered the necessary repair schedules: 10 % extra volume of material was therefore added to the overall material consumption of the respective floor for each predicted flooring system repair event projected. shows the functional unit adopted and data sources used for modelling the studied production processes.

Table 2 - Functional unit and inventory data source for materials/components studied

Construction materials and components	Functional unit	Data source
Concrete (fck 30MPa) [a]	1 m^3	Silva, 2006
Portland cement (CPIII-32) [a]	1 ton	Silva, 2006
Steel rebar (reinforcing steel)	1 ton	ELCD (European life cycle database)
Plywood formwork, Sand, Gravel	1 m^3	Ecoinvent
Wire Rods (prestressing steel)	1 ton	WorldSteel Association
[a] Concrete mix with cement type CPIII-32 (66% of ggbs as clinker replacement in cement)		

Service life is defined as the period between construction and the time to the first repair (tr), which may be determined using quantitative service life models for a particular element in a given environment. In this study, software Life-365 v.2.1 supported the prediction of life-cycle costs of reinforced concrete structures exposed to chlorides (Life-365 Manual, 2012). Parameters considered are structure type and dimensions; temperature, chloride exposure conditions; concrete mix characteristics, such as water-cementitious materials ratio (w/cm), and replacement of cement (%) by slag, Class F fly ash, or silica fume (SCMs); prestressing steel and steel rebar type, and *steel over concrete cross sectional area ratio* (%).

To enable comparison and level the life span to reach 40 years design life, LCA-based indicators considered the necessary repair schedules: 10 % extra volume of material was therefore added to the overall material consumption of the respective floor for each predicted flooring system repair event projected.

The minimum required service life of a residential building according to the Brazilian performance standard - NBR 15575:2012 - is 40 years (in April 2012). This was considered as the reference period for the LCC studies, being 2012 set as the reference year. LCC indicators have also considered the same repair schedule. Life-cycle cost was calculated as the sum of the initial construction costs and the discounted future repair costs disregarding labour, over the design life of the flooring system. Annual inflation rate of 5.06% and real discount rate of 9.75% were adopted. These figures respectively represented (in April 2012) 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. A 10-year interval between repairs was adopted, being the date of the first repair based on the service life predicted for each case study. The payback period shall be calculated based on such assumptions as well.

Important savings may however lie on the structural frame itself at any stage of its life cycle, or given by optimization of other building systems triggered by decisions regarding the structural frame. Levelling slab and beam heights, or adopting flat slabs, for instance, brings savings to energy and materials resources consumption due to optimized storey heights, reducing sealing / closing walls, and coating, heating and cooling, besides facilitating adaptability. Also, optimized columns layout provides less column density, enhancing net floor area, facilitating adaptability, improving parking spaces, which brings value to a building investment. Another example is designing for disassembly, which facilitates reuse and brings savings to demolition, recycling and materials resources consumption as well. Finally, the *local economy support indicator* was calculated based on availability of material suppliers within a 300 km-radius.

3. Results and discussion

Concerning the functional performance, Case study 2 (prestressed flat slab) presented the best performance for *span over slab ratio* and *column density indicators.* As to the *reuse potential indicator*, all three slabs were cast *in situ* and not designed for disassembly. Case study 1 (reinforced concrete waffle slab with 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 prestressed flat slabs used in Case studies 2 and 3. Furthermore, reinforcing steel has higher recycling market value than prestressing steel. Notwithstanding, the flooring system with no beams and longer spans (Case study 2) provides increased flexibility. Table 3 shows functional indicators results for all three case studies. The highlighted values are the best among alternatives.

Table 3 – Results of application of functional indicators to the three case studies

Functional Requirements	*Indicators*	*A typical floor*		
		Case 1	*Case 2*	*Case 3*
Structural safety	*span over height ratio (ℓ/d) [m/m]*	*24.3*	***39.7***	*32.8*
	applied stress over ultimate strength ratio (fc/fck) [kN/m²/ kN/m²]	*N/A*	*N/A*	*N/A*
Maintenance and constructability	*Reuse Potential (% volume prefabricated with connections for disassembly) [% volume]*	*0*	*0*	*0*
Flexibility / adaptability	*Column density: gross floor area over number of columns (m²/ nº), [m²]*	*17.8*	***30.6***	*19.8*
	Beam over slab height ratio, [m/m]	*1*	*1*	*1*

The results of service life prediction for the studied conditions (Table 4) confirm the need of a repair schedule for each alternative to ensure service lives of 40 years, which means that, under those conditions, designing by the Brazilian standard NBR 6118:2007 does not assure compliance to NBR 15575:2012. The environmental indicators per functional unit were multiplied by consumption of each material in mass or volume, including the material added by predicted repair events, and then divided by m^2 of structural area, in order to obtain each indicator per m^2. At typical floor scale, Case study 2 (15-storey building with no beams and prestressed concrete flat slabs) presented the best results for CF and EE, while Case study 1 (6-storey building with reinforced concrete waffle slabs) showed best results for bWF, ADP and Mc (Figure 1). Results for the whole superstructure showed a similar trend, except for CF, whose best result pointed to Case study 1 (Figure 2).

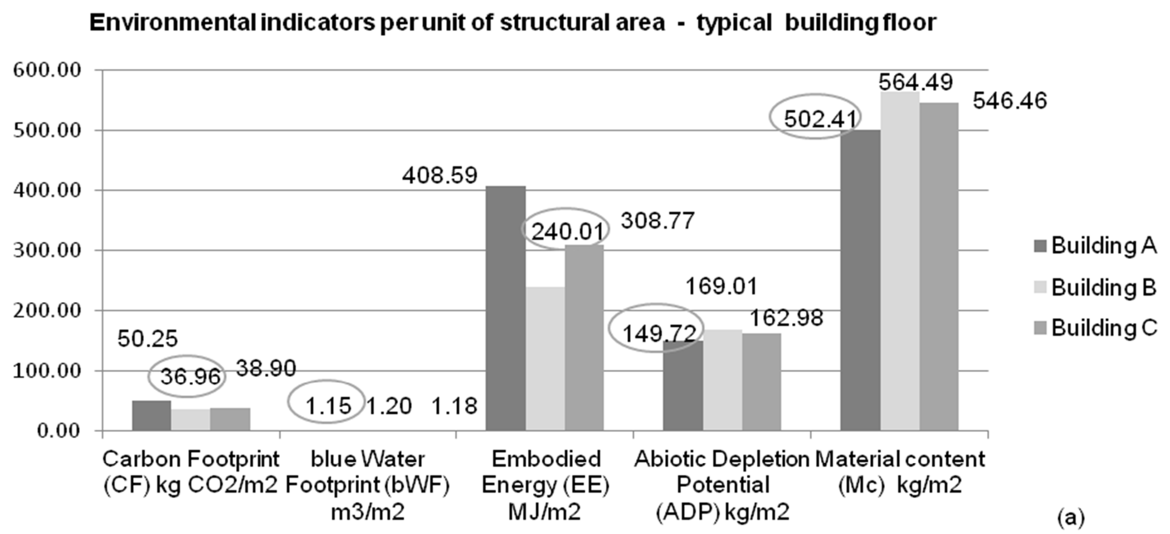

Figure 1 - Results of environmental indicators application to Case studies 1 (Building A), 2 (Building B) and 3 (Building C), for a typical floor.

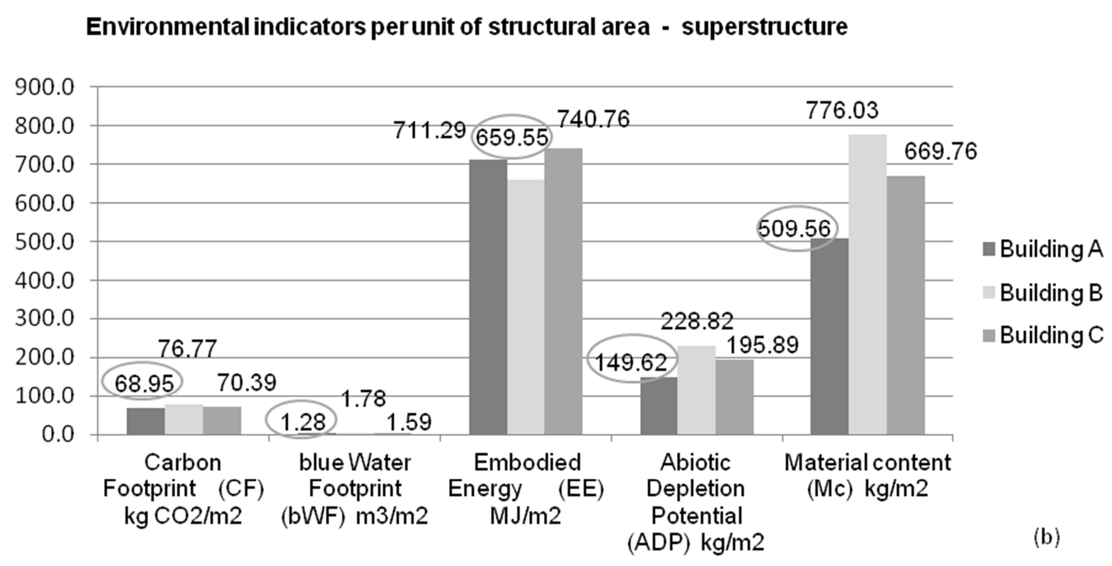

Figure 2 - Results of environmental indicators application to Case studies 1* (Building A)*, 2* (Building B) and *3* (Building C), *for the whole superstructure.

The service life estimated for the three case studies was similar because they had identical characteristic strength, mix composition and nominal concrete cover. The same applies to the repair costs/m^2, obtained through a simplified default estimate despite having taken into account different costs of reinforcing and prestressing steel, and different steel percentages in the cross section of reinforced and prestressed concrete slabs. Table 4 presents values of *LCC indicators* for the three case studies, showing the best results for Case study 3.

Table 4 - Service life and life cycle costs estimated for the three case studies

Case studies	Typical floor description	Estimated Service life [years]	Life cycle costs (LCC) US $ /m$^2_{structural\ floor\ area}$						
			Initial costs					Maintenance / Repair costs	Total life cycle costs
			Plywood formwork	Concrete	Rebar	Prestressing steel	Total initial costs		
1	RC waffle slab	11.7	2.93	17.48	20.07	0.00	40.47	57.85	98.32
2	PC flat slab	11.2	2.94	20.00	9.44	6.73	39.10	57.85	96.95
3	PC flat slab	11.2	2.79	19.33	8.53	5.35	36.00	57.85	93.85

A complete *payback* indicator calculation shall address the savings provided by *(i)* the lowest column density of Case study 2 (Table 3) concerning parking spaces and typical floors flexibility, *(ii)* the 9.5cm reduction from a 27.5cm-thick waffle slab (Case study 1) to 18cm-thick prestressed flat slabs of case studies 2 and 3 to envelope plaster and coating consumption, and *(iii)* the smallest dead weight of Case study 1 waffle slab (equivalent to a 14.7cm-thick flat slab) to whole superstructure sizing and foundations. Monetary figures and flows related to such additional data are usually not readily available at the structural design offices, and therefore were not provided for the studied cases. Implementation of continuous value engineering techniques during design would enable reasonably accurate estimation and allow the recommended integrative approach.

For *local economy support indicator*, the flooring system of a typical floor in Case study 3 presented the best result, with local materials responding for 59% of total material costs, followed by Case studies 2 (56%) and 1 (48%), respectively (Table 5).

Table 5 – Results of application of local economy support indicator to the three case studies

Indicator	**Typical floor**		
	Case study 1	**Case study 2**	**Case study 3**
Local economy support [% in costs]	48	56	**59**

4. Concluding remarks

Discrepancies or deficiency of national and international reference data for insertion in LCA platforms demand the use of different databases for modelling the materials /components production cycle. Reinforcing steel, plywood formwork (processes adapted within different databases by switching into the Brazilian energy mix), and prestressing steel (production cycle taken from WorldSteel database with no possibility of energy mix adaptation) are examples. This may compromise accuracy and reliability of LCA-based indicators application.

Other strategies for increasing concrete structures service life than to predict a repair schedule were perceived during Life-365 software modelling, such as enhancing cover of reinforcement; using chemical corrosion inhibitors, membranes or sealers; specifying stainless steel; or using silica fume as mineral admixture. Considering the current Brazilian construction practice, only the use of chemical corrosion inhibitors and silica fume seem reasonable.

At whole superstructure scale, the EE indicator pointed to Case study 2 (prestressed concrete flat slab) as the best solution from the environmental viewpoint, while ADP, Mc, bWF and CF indicators pointed to Case study 1 (reinforced concrete waffle slab and beams) as best performing flooring system. Concerning the economic and functional indicators, prestressed concrete flat slabs performed best. Therefore, next research steps include adoption of a multi-attribute analysis method to define relative importance of indicators in each dimension structuring them in a decision matrix assembling different weighting scenarios, to streamline choice of a single solution, whenever indicators show contrasting trends.

Proceeding with the analysis of a typical structural floor *in lieu* of the whole building structure – analogously to structural design common practice - seems to be potentially valid. Amongst the five environmental indicators, four of them showed similar trends at both typical floor and whole superstructure scales. CF indicator shifted trend when zooming into typical floor scale. *The local economy support indicator* provided useful information when applied to a typical floor. Due to the limited number of case studies, these findings are promising but still exploratory. Enlargement of case study library in future studies will provide robustness to analysis and allow in-depth statistical treatment and more assertive conclusions.

Exploring the most cost-and environmentally-effective strategies for increasing concrete structures service life exposed to a marine environment is also of interest. 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.

Acknowledgements

The authors would like to thank the Brazilian Coordination of Improvement of Higher Education Personnel (CAPES), the National Council of Technological and Scientific

Development (CNPq) and CPFL Energy / ANEEL R&D Funding line for their financial support.

References

Associação Brasileira de Normas Técnicas – ABNT. NBR 15.575:2012. Edificações habitacionais de até cinco pavimentos – Desempenho. Válida a partir de 12.04.2012. RJ, Brasil *(in Portuguese).*

__________ABNT. NBR 6118:2007. Projeto de Estruturas de Concreto - Procedimento. Versão corrigida, em vigor a partir de 21.06.2007. 221p. RJ, Brasil *(in Portuguese).*

CRISP – Construction and City Related Sustainability Indicators (2005).EC FP5 CRISP indicator analysis PeBBu generic task 2, *final report*. CIBdf, the Netherlands.

Dobbelsteen, A.A.J.F., Arets, M. J. P. and Linden, A.C.V.D. (2005) *Smart sustainable office design–effective technological solutions, based on typology and case studies*. In: YANG, J. et al. Smart & sustainable built environments, Wiley-Blackwell, p. 3-13.

Dobbelsteen, A.A.J.F., Arets, M. and Nunes, R. (2007) Sustainable design of supporting structures. Optimal structural spans and component combinations for effective improvement of environmental performance. *Construction Innovation*, v.7.n. 1. p.54-71, Emerald.

Energy saving through promotion of life cycle assessment in buildings. ENSLIC-ARMINES - WPR21-Rev5-State-of-the-art for use of LCA in building sector (2009). 75p.

Haapio, A., Viitaniemi, P.(2008) Environmental effect of structural solutions and building materials to a building. *Environmental Impact Assessment Review*, v.28, p.587-600.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION – ISO. Standard 6240. Performance standards in building - Contents and presentation. 1980. Genève, Switzerland.

________ISO. Standard 6241. Performance standards in building - Principles for their preparation and factors to be considered. 1984. Genève, Switzerland.

________ISO. Standard 14040: Environmental Management – Life Cycle Principles and Framework. Switzerland, 2006.

________ISO/TS. Technical Specification 21929-1. Sustainability in building construction -- Sustainability indicators -- Part 1: Framework for development of indicators for buildings. 2006. Genève, Switzerland.

________ISO. Standard 21931-1. Sustainability in building construction– Framework for methods of assessment of the environmental performance of construction works - Part 1: Buildings. 2010. Genève, Switzerland.

Kellenberger, D., Althaus, H. (2009) Relevance of simplifications in LCA of building components. *Building and Environment,* v. 44, n. 4, p. 818-825.

Laefer, D. F., Manke, J. P. (2008) Building reuse assessment for sustainable urban reconstruction. *Journal of Construction Engineering and Management*. Vol. 134, n. 3, March.

Life-365 Service life prediction model, v. 2.1 – *User's Manual*. January, 2012.

Lorenz, E. (2012) We cannnot have sustainability without durability. *PCI Journal*. Jan-Feb, 2008. (Available on line at, http://www.pci.org/view_file.cfm?file=JL-08-january-february-2.pdf. [Accessed on 08/23/12]).

Luetzkendorf, T., Hajek, P., Lupisek, A., Immendoerfer, A., Nibel, S., Hakkinen, T. (2011) Next generation of sustainability assessment – top down approach and stakeholders needs. In: World Sustainable Building Conference - SB11 HELSINKI. *Proceedings*, theme 4, p.359-374, Finland.

Moon, K. S. (2009) Sustainable design of tall building structures and façades. In: SASBE 2009. *Proceedings*… v.1, pp.1- 8.

Nunem, H; Mooiman, A. (2011) Improved service life predictions for better life cycle assessments. In: SB11 HELSINKI. *Proceedings*, theme 1, pp.240-250. Finland.

Oliveira, F. R. M.; Silva, V. G.; Silva, M. G. (2011) Towards Integration of environmental, functional and economic indicators for envelope and structural frame selection: proposal for discussion at the conceptual design stage. In: World Sustainable Building Conference - SB11 HELSINKI, 18-21.oct.2011. *Proceedings*, theme 4 - Sustainable processes and eco-efficient technologies, p. 502-509, Finland.

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT.(2003) Environmental Indicators: Development, Measurement and Use. OECD, Paris.

Reap, J., Roman, F., Duncan, S., Bras, B. (2008) A survey of unresolved problems in life cycle assessment. Part 1: goal and scope and inventory analysis. *International Journal of Life Cycle Assessment*.v.1, p.1-11. May.

Silva, M.G. (Coordinator). (2006) Concreto de alto desempenho com elevados teores de escória de alto-forno: estratégia para consolidar o mercado da escória de alto-forno em cimentos e concretos. Núcleo de Excelência em Escórias Siderúrgicas (NEXES). Centro Tecnológico, Universidade Federal do Espírito Santo. (*Research report*, in Portuguese).

SUPERBUILDINGS. FP7 Cooperation Programme. (2011) *NEWSLETTER, 2* July. (Available on line at, http://cic.vtt.fi/superbuildings/. [Accessed on 02/23/2012]).

UNITED NATIONS. UN ST/ESCAP/2561 (2009) – *Eco-efficiency indicators: measuring resource-use efficiency and the impact of economic activities on the environment*. 28p. Thailand. (Available on line at, http://www.unescap.org/esd>. [Accessed on August/2010]).

Zabalza-Bribian. I., Capilla, A.V., Uson, A.A. (2011) Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Building and Environment*, v.46, p.1133-1140.