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# Optimization of reinforced concrete columns according to different environmental impact assessment parameters

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ABSTRACT

In addition to economic gains, the use of optimization strategies in the development of a structural design can reduce the consumption of materials whose extraction, manufacture and transport cause large environmental damage, as occurs with reinforced concrete inputs. The aim of the present study was to optimize the monetary and environmental costs associated with pieces of rectangular reinforced concrete columns submitted to uniaxial bending and compression loads, using the harmony search algorithm, which consists of a meta-heuristic approach analogous to the process of attaining the best musical harmony. Therefore, in addition to taking into account the purchasing costs of materials in the structural optimization process, analyses were conducted to determine the environmental costs of each input, estimated from the life-cycle analysis. The sizes of concrete section and the amount and gauges of the structures, as well as concrete strength, were used as variables. The columns were checked as to ultimate and serviceability limit states following the ABNT NBR 6118/07 Brazilian standard. Several indicators were used for environmental cost minimization, and the results were compared to those obtained from conventional sizing processes as well as from other optimization methods. In general, even with structure optimization to minimize monetary costs, important reductions in environmental costs are obtained, regardless of the indicator used for impact analysis, thus yielding cross-sections with different features.


## 1. Introduction

The impact of reinforced concrete structures on environment is significant and has increased year after year. The world production of cement, major component of concrete, reached 1.6 billion tons/year in 2001, which corresponds to approximately 7% of the global load of carbon dioxide released into the atmosphere [1,2]. In 2010, according to the *International Cement Review*, the world production of cement rose to around 3.3 billion tons/year, which means an increase over 100% in almost 10 years and has further increased its impact on the environment [3].

A large amount of aggregates (sand and crushed stone) is extracted from natural deposits for concrete production. Besides resource depletion, this eventually plays havoc with extraction sites, damaging the soil, water resources and local flora and fauna. Cement production also requires the extraction of clay and lime materials, with similar devastating impacts. In addition to the exhaustion of natural resources and the generation of greenhouse gases, concrete production consumes water and energy and causes indirect impacts, for instance, from carbon dioxide emissions during the transportation of inputs and of plant-mixed concrete to the construction site [1,4].

The compilation and assessment of inputs, outputs and of potential environmental impacts of an activity or production process over its life cycle is known as life cycle assessment (LCA). LCA identifies, quantifies and assesses raw material extractions (inputs) and emissions into the atmosphere (outputs) of a production system, from cradle to grave, in order to determine potential impacts on natural resources, on environment and on human health. That is, the assessment starts with raw materials, goes through manufacture, transportation, use and maintenance, and ends with final disposal. Different methods for environmental impact analysis are described in the literature and they tend to be customized to the local reality of their countries of origin.

Despite the large consumption of energy for concrete manufacture, the emissions of greenhouse gases and, mainly, the extensive extraction of natural resources, several researchers assert that between steel and reinforced concrete structures, the latter ones are better as they cause fewer environmental impacts [5–7]. According to Denilson and Halligan [8], concrete buildings, due to their thermal delay in relation to steel buildings, can have a lower energy consumption. For Struble and Godfrey [9], who compare the environmental impact of reinforced concrete and steel beams used for the same purpose, the former consume less energy and cause less

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pollution to water resources than the latter. The higher carbon dioxide emission from concrete, compared to steel, does not exceed 10%, and in terms of mineral extraction, that of steel is about 60% smaller.

However, it is unwise to categorically affirm that reinforced concrete is more sustainable than steel since, depending on the peculiarities of each region or country, materials can have quite different life cycle costs. Moreover, it is essential to make comparisons using the same design characteristics, as one cannot compare environmental impact for the same unit of volume of materials as their structural performance differs [10].

In any case, reduction in materials consumption is crucial for greater sustainability of civil construction, regardless of the structural system used. And because concrete is an extensively used material, it would be interesting to reduce its consumption as much as possible and, therefore, its environmental impact. Sustainable development postulates that the use of non-renewable materials should be considerably reduced [11].

Based on that, it is possible to say that structural optimization is closely related to sustainable development, as it is directly associated with economic and environmental issues. The design of infrastructure systems based on the life cycle of materials maximizes the returns of available capital and also of the available natural resources [1,12].

Many works in the literature deal with the life cycle assessment of reinforced concrete and steel structures [2,6,9,10,13]. Most of them simply estimate the overall environmental impacts of energy consumption and emissions of carbon dioxide, sulfur dioxide, nitrogen oxide, among others. That is done for buildings as a whole or for specific structural elements. There are also studies that only estimate the impacts for a given unit of mass or volume of the analyzed inputs.

Some recent research studies have also dealt with structural optimization based on environmental costs. Some examples include the works of Payá-Zaforteza et al. [14,15], Yeo and Gabbai [16] and Yepes et al. [17].

In this context, the present paper sought to propose the minimization of the environmental costs associated with the section of rectangular reinforced concrete columns submitted to uniaxial bending and compression loads using different parameters for environmental impact assessment. The ABNT NBR 6118/07 Brazilian standard – concrete structure design – Procedures [18] was used for the sections. Optimization was obtained by the heuristic method known as Harmony Search, initially proposed by Geem et al. [19], based on the observation that a musician's goal is the search for a perfect harmony.

## 2. Checking the strength of reinforced concrete columns

The sizing of reinforced concrete columns submitted to bending and compression is usually determined by dimensionless interaction diagrams, as shown in Montoya et al. [20], or by the use of specific tables for the sizing of the sections.

The process of evaluating the sections submitted to uniaxial bending and compression loads begins with determining the normal strength ($N_{sd}$), the bending moment ($M_{sd}$), as well as the cross-section used for the concrete, whose diameters and arrangement of steel bars should also be known. The acting forces ($N_{sd}$, $M_{sd}$) are obtained by multiplying the characteristic strengths by the respective partial safety coefficients ($\gamma_f$), provided by the Brazilian standard for different actions and combinations involved in the design. The ultimate strengths are obtained by the following equilibrium equations:

$$N_{rd} = \int_{AC} \sigma_{cd} \cdot dA_c + \sum_{i=1}^{n} A_{si} \cdot \sigma_{sdi} \quad (1)$$

$$M_{rd} = \int_{AC} \sigma_{cd} \cdot x_c \cdot dA_c + \sum_{i=1}^{n} A_{si} \cdot \sigma_{sdi} \cdot x_{si} \quad (2)$$

where $N_{rd}$ is the normal ultimate strength; $M_{rd}$ is the ultimate moment; $\sigma_{cd}$ is the stress in the area of compressed concrete $A_c$; $\sigma_{sdi}$ is the stress in the area of steel $A_{si}$; $x_c$ is the distance from the center of the compressed steel area from the center of gravity of the section; and $x_{si}$ is the distance from steel bar $i$ from the center of gravity of the section.

To solve these equations, it is necessary to know the depth of the neutral axis ($x_0$), as well as the slope $\alpha$ relative to axis $\times$ (perpendicular to the largest dimension of the section) and the amount of steel used ($A_s$). The determination of the neutral axis ($x_0$) consists of an iterative process, in which an attempt is made to equal normal ultimate strength values with normal working strength values for a given slope $\alpha$. This is accomplished by Eq. (3), where $f(x_0) = 0$.

$$f(x_0) = N_{sd} - A_{cc} \cdot \sigma_{cd} - \sum_{i=1}^{n} A_{si} . \sigma_{sdi} \quad (3)$$

Hence, the normal ultimate strength ($N_{rd}$) should be equal to the normal working strength ($N_{sd}$) applied to a cross-section with known reinforcements. Depth $x_0$ of the neutral axis in relation to the compressed border of the cross-section, lies on the interval $[0,\infty]$, and it is parallel to the axis to which the bending moment ($\alpha = 0$) is applied in the case of uniaxial bending and compression loads.

After the depth of $x_0$ of the neutral axis is known, Eqs. (1) and (2) take the following form:

$$N_{rd} = A_{cc} \cdot \sigma_{cd} + \sum_{i=1}^{n} A_{si} \cdot \sigma_{sdi} \quad (4)$$

$$M_{rd} = S_c \cdot \sigma_{cd} + \sum_{i=1}^{n} A_{si} \cdot \sigma_{sdi} \cdot x_{si} \quad (5)$$

where $A_{cc}$ is the area of compressed concrete; $S_c$ is the static moment of the compressed concrete area of the section.

After calculation of the ultimate moment ($M_{rd}$), it is then necessary to check whether it is greater or at least equal to the working moment ($M_{sd}$). Otherwise, the section must be resized.

## 3. Harmony search

Optimization is an important tool in the decision-making process and in the analysis of physical systems. Optimizing basically consists in finding the best possible solution to a given problem, which may be defined mathematically through functions, with one or several objectives. This mathematical modeling may or may not meet certain requirements, which are represented by constraints. In the case of structural optimization, the aim, in general, is to minimize the costs of a structure, meeting the basic safety principles, the ultimate and serviceability limit states and any other technical requirements.

The classic mathematical programming methods, which consist of deterministic algorithms, often include the calculation of first-order or partial second-order derivatives. Although conveniently used for unimodal problems, and quite rapid and efficient, mathematical methods pose several challenges in more complex problems, making their use inappropriate for most optimization problems in science and in engineering. On the other hand, probabilistic or heuristic methods do not cling so easily to local extremes, as the search occurs within the whole feasible region available, and are therefore regarded as global optimization algorithms, dealing properly with both continuous and discrete parameters.