Cost Optimization of RC Beams Considering Steel Rebar Losses

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Abstract. Optimization techniques are an efficient tool for developing structural projects. By seeking the rational use of available resources, they can not only reduce costs but also the impact on the environment. In this sense, it is interesting that these techniques are effectively incorporated throughout the process, including the construction stage. For example, in the design of reinforced concrete structures, an additional 10 percent of steel consumption is usually foreseen due to losses from cutting rebar, which is supplied in standard lengths on the market. These losses can be significantly reduced if the bars are cut according to an optimized plan. This study aims to combine the optimization of the cost of reinforced concrete beams with the minimization of losses due to the cutting of steel bars. Initially, the two optimization problems were implemented separately and adopted sequentially, using the Harmony Search Optimization Method and the Simplex Method, respectively. Simulations were then carried out to illustrate the economy obtained from the losses optimization, as well as to assess the influence of factors such as the number of beams and the number of gauges on losses and final costs. Preliminary results evidenced the influence of the detailing in the final costs, and that the reduction in the number of different gauges positively influences losses and constructive aspects. In a second stage, the study aims to integrate the two problems so that the reduction of losses can be optimized even during the design of the structure.

Keywords: Optimization; one-dimensional cutting; loss reduction; reinforced concrete; beams

1 Introduction

The integration of optimization techniques from the earliest stages of design can result in significant improvements in material efficiency and cost reduction, as well as promoting greater durability and resistance of structures [1, 2]. Recent research into optimization techniques has highlighted the importance of making rational use of available resources, with a focus on reducing costs and the environmental impact produced by structures, e.g. [3, 4]. Furthermore, it is interesting that these techniques can be effectively incorporated throughout the process, including the construction stage.

Reducing steel losses when cutting rebar, supplied in standard lengths, is a significant challenge in the construction industry. Recent studies [5,6] address this problem, highlighting that optimizing cutting processes can considerably reduce material waste by maximizing the use of rebar and minimizing leftovers, thus contributing to more efficient resource management and cost reduction in the sector.

The problem of generating cutting patterns (cutting-stock problem) involves cutting stored objects, whose sizes and quantities are known, to satisfy a demand for items with specific sizes and quantities. The objects must be cut following patterns that determine different ways of arranging the items within the objects to minimize material loss. Solving the problem involves two distinct phases, the first being the definition of possible cutting patterns, and the second defining which patterns will result in the least losses. Generally, these two problems are approached, both in practice and in the literature, independently and successively.

The optimization of reinforced concrete beams, due to their great importance and usefulness, has been addressed by several researchers [7-9]. In general, the formulations aim to minimize the cost, considering the contributions of concrete, steel, and formworks, with or without the labor involved. However, the cost of materials only considers what is effectively used in the structure, disregarding any waste resulting from the construction process.

This study aims to optimize the cost of reinforced concrete beams by minimizing losses due to cutting steel bars. To do this, the cost of the beam is initially minimized. Next, the loss obtained from the one-dimensional cutting problem is added to the cost of the steel. Initially, the two optimization problems are approached independently and applied sequentially using the Harmonic Search Optimization Method and the Simplex Method. In the sequence, numerical simulations were then carried out to assess the influence of factors such as the number of beams and the number of gauges on losses and final costs.

This paper is organized as follows. The first section presents a brief introduction to the study. The second section presents the formulations adopted, with the simulations and preliminary results described in the third section. Finally, the fourth section describes the work's main conclusions and future stages.

2 Problem Formulation

2.1 Beams optimization

As previously mentioned, the first part of this study consists on the optimization of the reinforced concrete building beams. Among several formulations, it was adopted the study of Medeiros and Kripka [7] on the cost minimization of reinforced concrete building grillages, considering the cost of concrete C_c, steel C_A, and formwork C_F. Thus, the objective function C_t (total cost) of the optimization problem was obtained by adding the products of the unit cost of each material and the corresponding quantity consumed in the beam being: $P_A + P_{ASW}$ the weight of longitudinal and transverse steel, respectively, A_F the total formwork area and V_C the volume of concrete, as in eq.(1):

$$C_t = \left[\left(P_A + P_{A_{sw}}\right).C_A\right] + (A_F.C_F) + (V_C.C_C) \tag{1}$$

The problem variables are the height h of the beams, with the steel areas obtained from these values. The variables of the problem are discrete and can assume values with an increment of 5cm, according to the current practice. The constraints involve the verification of ultimate and service limit states, according to Brazilian standard ABNT NBR 6118/2023 [10], as well as constructive aspects, and are listed in eq. (2) to (7).

$$\delta \leq \delta_{lim} \tag{2}$$

$$\frac{M_{As\prime}}{M_{As}} \leq 0{,}30 \tag{3}$$

$$0{,}15\%\ A_C \leq A_s + A'_s \leq 4\%\ A_C \tag{4}$$

$$V_{Sd} \leq V_{Rd2} \tag{5}$$

$$V_{Sd} \leq V_{Rd3} \tag{6}$$

$$\rho_{SW_{min}} = \frac{A_{SW}}{b_w S} \geq 0{,}2\,\frac{f_{ctm}}{f_{ywk}} \tag{7}$$

The first constraint, in eq.(2), is related to service limit states, where the maximum displacement, considering long-term effects, must respect the limit. Regarding flexural reinforcement, the constraints are: the ratio between the fractions of the bending moment absorbed by the compression ($M_{AS'}$) and tension reinforcements (M_{AS}) should not exceed 30% (eq. (3)) to prevent concentration of reinforcements; the minimum reinforcement ratio (ρmin) should be larger than the ratios defined in the standard, whereas the maximum ratio should be equivalent to at most 4% of the cross-section area (eq.(4)). To shearing, the strain concrete should withstand in compressed struts (V_{Rd2}) should be greater than the respective stress (V_{Sd}), as outlined in eq.(5), and the strength of concrete and reinforcements in the tensioned struts (V_{Rd3}) should be larger than the working stress (V_{Sd}), as in eq.(6). The last constraint (eq.(7)) refers to the minimum reinforcement ratio, considering shear and torsion.

The problem of optimizing the component beams of a grid has a non-convex nature, which makes it difficult to obtain optimized results using mathematical methods even for a small number of design variables. To overcome this difficulty, the use of heuristics has proved to be a preferable option, as these techniques provide satisfactory solutions with little computational effort, making the optimization process more feasible and practical in industrial contexts. Among optimization techniques, Harmony Search (HS) stands out as a metaheuristic capable of achieving optimal results with fewer iterations and smaller populations than other methods, provided that its internal parameters are well-tuned to the specific problem. The method draws inspiration from jazz musical improvisation, where musicians experiment with new note combinations for each instrument, using prior knowledge or repeated attempts. In this analogy, the instruments symbolize the variables of the optimization problem, which must be skillfully combined to achieve the perfect harmony or the global optimum. Since the publication of the original method by Geem et all in 2001 [11], improvements have been proposed aiming to increase the algorithm's performance, such as the Improved Harmony Search (IHS), one of the most notable. In this study, an extension of IHS proposed by Medeiros and Kripka [12] is adopted. One of the main contributions of this method called Modified Improved Harmony Search (MIHS) is the possibility of reinitialization of the population (Harmony Memory) to improve its diversity.

2.2 Cutting-stock optimization problem

The one-dimensional cutting problem, also known as the cutting-stock problem, is a classic challenge in operations research and combinatorial optimization. This problem consists of cutting long objects, such as steel bars or wood, into smaller pieces to meet a specific demand while minimizing material losses. According to the theory of Gilmore and Gomory [13], the mathematical formulation of the problem can be represented as an integer linear programming problem, where the objective is to minimize the amount of material wasted by cutting the bars into smaller pieces. Formally, the objective function can be expressed as minimizing the total material waste W, where the variables x_i are defined as the number of times cutting pattern i is used and w_i is the waste associated with the pattern, as described in eq.(8). The constraints represented in eq.(9) state that the total quantity of items produced is equal to the demanded quantity d_i. In this equation, a_{ij} represents the number of times order j appears in the pattern i. The constraint expressed in eq.(10) indicates that the number of times a pattern is used must have an integer and non-negative value. It is important to notice that the application of the described formulation implies the previous obtention of the cutting patterns.

$$\text{Min W}= \sum_{i=1}^{n} w_i . x_i \tag{8}$$

$$\sum_{j=1}^{n} a_{ij} . x_i = d_j \tag{9}$$

$$x_i \in Z^{+} \tag{10}$$

The simplex method, introduced by George Dantzig in 1947, is a widely used technique for solving linear programming problems. The efficiency of the simplex method is remarkable in practice because, although the theoretical worst case can take exponential time, it generally finds the optimal solution in a number of iterations that is polynomial concerning the number of variables and constraints. This method operates by moving along the vertices of the feasible region of a linear function, and each step seeks an improvement in the objective function until the optimal solution is reached. Due to its robustness and practical efficiency, the simplex method remains a fundamental tool in operations research and optimization, being implemented in various commercial and academic software to solve large-scale problems.

3 Numerical Simulation

This study aims to optimize the cost of structures by taking into account losses during the design and detailing process. In this preliminary study, these stages are being considered sequentially, to verify the effect of detailing on losses and, consequently, on the final cost of the structure. Two different optimization methods were adopted: the Harmony Search to beams optimization, and the Simplex Method to the determination of the cutting losses.

To illustrate the procedure employed, the following are the results obtained from the analysis of a single beam, component of a building grillage adapted from the work developed by Kripka, Medeiros, and Lemonge [15]. The dimensions of the spans and loads are shown in Figure 1.

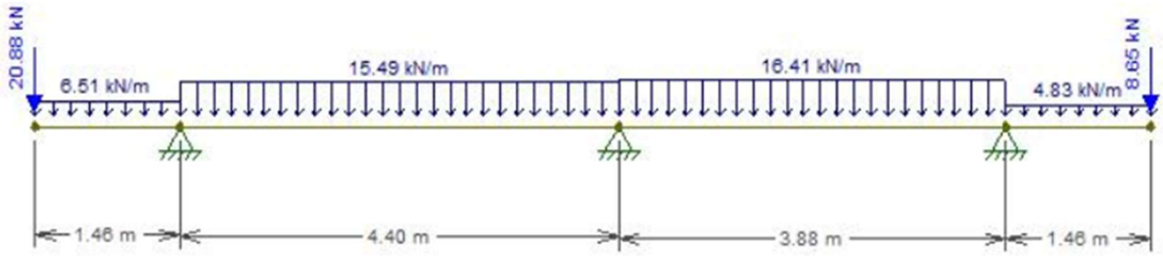

Figure 1. Example: beam dimensions and loads

To optimize the beam's cross-section, the following data were adopted: characteristic concrete strength *fck*=25MPa, concrete cover *c*=3cm, and beam width *bw*=15cm. The unit costs, in Brazilian currency (R$), were considered the same as the original work [15], being: CA-50 steel bars = R$3.97/kg, CA-60 steel bars = R$3.89/kg, formworks = R$8.68/m^2, and concrete = R$233.55/m^3.

Considering the same beam section height for all spans, an optimized height of 40cm was obtained, corresponding to a total cost of R$393.36. It should be emphasized that this result is obtained considering the required steel area, and the reinforcement should be detailed based on this value. The beams were designed using PTC MathCAD, while AutoCAD was used for detailing and quantity surveying. Figure 2 shows the reinforcement detailing.

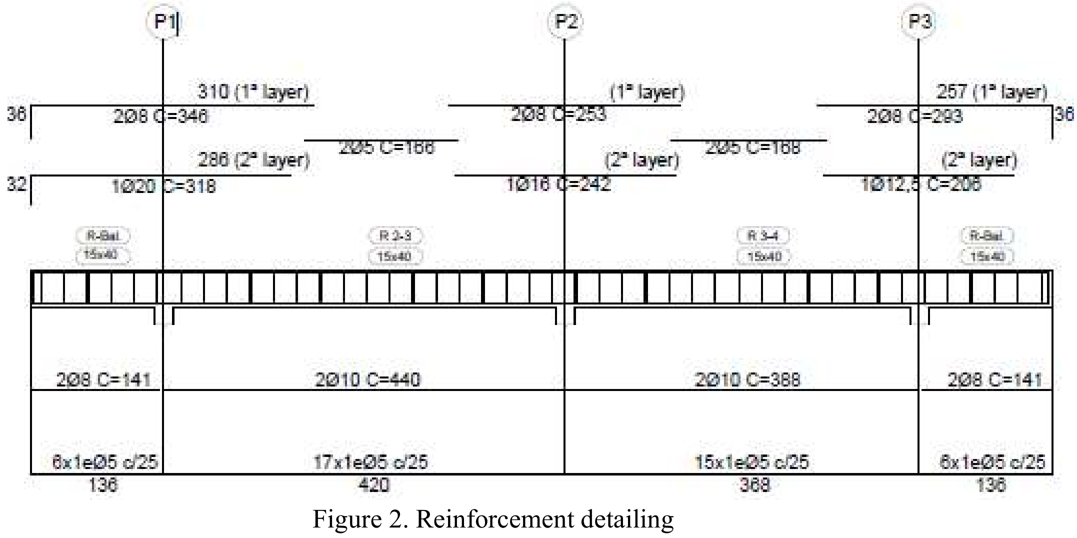

Figure 2. Reinforcement detailing

Based on the quantity survey, it is usual to consider an increase of 10% over the calculated reinforcement as the loss resulting from the bar-cutting process. However, the effective loss caused during the cutting process varies depending on the demand for segments and the standard size of rebar commonly found on the market (usually 12m). Considering the different sizes and quantities required for each gauge, numerous cutting patterns can be determined. Indeed, considering that the number of patterns increases non-exponentially, it is almost impossible to predetermine all the existing patterns to large problems. In the present example, the patterns were generated, from the beam detailing, by a greedy heuristic called FFD (or First Fit Decreasing). According to this strategy, all demanded items are sorted in descending order concerning their lengths, and the largest item in the pattern is used the highest possible number of times without exceeding the demand. If the selected item does not fit the pattern anymore, the second largest item is selected, and so on [16]. The solution to the cutting stock problem was generated using a Python implementation of Simplex Method, and compared to results obtained with Excel Solver and Cutlistoptimizer (https://www.cutlistoptimizer.com). It was observed that the results are strongly dependent on the number and quality of the patterns generated.

Table 1 presents the patterns generated to ø8mm bars, indicating the losses regarding 12m length bars and the total demand of each length.

Table 2. Cutting patterns generated to ø8mm bars

Pattern	3.46m	2.93m	2.53m	1.41m	Losses (m)
1	1	0	1	4	0.37
2	2	0	2	0	0.02
3	2	0	0	3	0.85
4	1	0	2	2	0.66
5	0	2	2	0	1.08
6	1	2	1	0	0.15
7	1	1	2	0	0.55
8	0	2	0	4	0.50
Demand	**2**	**2**	**2**	**4**	

The result of the cutting problem for the 8mm gauge indicated the use of one bar of patterns 1 and 6, illustrated in Figure 3 (for better visualization, the diameter of the bars is represented out of scale). These patterns result in a total loss of 0.52m, or 2.17%.

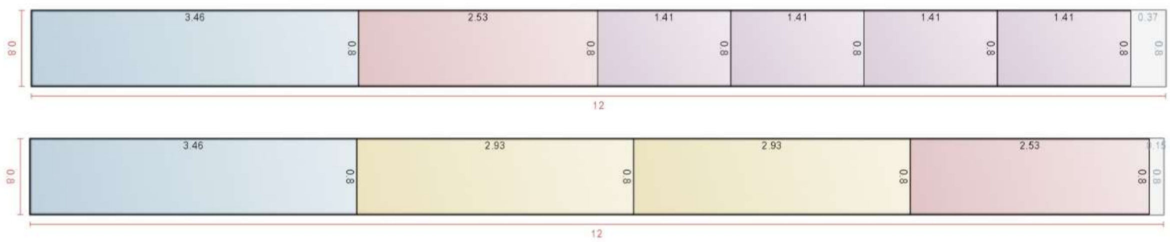

Figure 3. Optimized cutting patterns 1 and 6

Regarding the other gauges used in the beam, a similar procedure was adopted. For the bigger gauges, it was not possible to make any significant improvement, as the number of items demanded is quite small. It is important to emphasize that once structures with a growing number of elements are analyzed, greater percentage savings can be obtained due to the greater number of possible patterns. This stresses the importance of applying optimization techniques and considering the scale of production when planning cutting processes in engineering projects, ensuring more efficient management of resources and a reduction in operating costs. On the other hand, a larger number of items to be cut can make the problem of generating cutting patterns quite complex. This highlights the need to define optimized strategies for obtaining more efficient patterns.

Following the study, a new detailing of the reinforcements was made for the same beam aiming to reduce the number of different gauges. This detailing changed the 20mm gauge by a 12.5 and a 16mm steel rebars. Although it represented a small reduction in the total weight of steel (about 2%), this change allowed the elimination of the 20mm bar and the better use of bars with reduced gauge (and lengths). To the simple structure of the example, it represented a 9% reduction in the number of bars needed, considering all gauges and the loss minimization.

4 Conclusions

The application of optimization techniques is an extremely efficient tool for designing structures. This study proposes optimizing the cost of reinforced concrete beams by also taking into account the cost of losses resulting from the steel bar-cutting process. In the current stage of the study, the problems of section optimization and loss minimization were addressed sequentially.

To compare different structural solutions, it is necessary to consider certain variables, such as the cost of the material, which includes the price per meter of the different gauges used, material losses (which are calculated as the amount of material wasted after the proper cutting), labor, and assembly time. More complex detailing can increase labor costs and the time required for assembly, as well as structural performance, characterized by the beam's ability to meet load requirements safely and efficiently.

This paper investigated the influence of the detailing on the total losses. In the example studied an initial detailing was made based on the optimized height, and the losses were calculated for each gauge. After this, a new detailing considered a reduction in the number of different gauges was considered. It was observed that the reduction in the number of gauges corresponded to a significant reduction in the number of steel bars needed (11 to 10, or about 9%). Although demanding the study of more complex structures shall be evaluated to generalize the conclusions, these results point out the importance of the integration of dimensioning and detailing phases to the reduction of the total cost of the structure.

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