A Sustainable Approach for Reversing the Structural Design Process of Steel Structures: From the Traditional Minimum-Weight Approach to the Cutting Losses Minimization

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A Sustainable Approach for Reversing the Structural Design Process of Steel Structures: From the Traditional Minimum-Weight Approach to the Cutting Losses Minimization

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Abstract. In this research, a Genetic Algorithm (GA) has been developed and the well-known one-dimensional bin packing problem (BPP) has been implemented within the structural optimization process. The Objective Function formulation lies in a marked change of the paradigm in which the target function is represented by the amount of steel required by the factory instead of the structural cost (e.g. weight). The best design is obtained by varying the geometry properties of the members and the cross-section assignation ensuring optimal stock of existing elements. Finally, the structural cost and the Carbon emission are calculated for a spatial reticular dome. The mass of the waste with respect to the mass of the stock, M_{waste}/M_{stock}, is evaluated by adopting both the cutting Stock approach and the traditional approach. The former leads to a waste saving that is almost twice that obtained from the latter. However, no significant differences in terms of carbon emission can be observed by comparing the two approaches.

Keywords. Optimization, genetic algorithm, cutting stock problem, cutting waste, sustainability, steel

1. Introduction

In the last decades, the scientific community has been actively engaged in addressing the imperative of reducing the costs associated with structures through the strategic management of material selection, fabrication methods, and maintenance expenses [1]. Within the context of structural optimization (SO), there has been a significant focus on the minimization of material costs, with the overarching goal of creating slender structures that

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optimize resource utilization [2]. Conventional practice among researchers and practitioners in this field involves the optimization of structural design costs, while concurrently adhering to safety guidelines stipulated by relevant standard regulations [3]. It is noteworthy that a substantial portion of the expenditures can be attributed to material wastage resulting from the cutting process, particularly in the context of metal structures. In other words, failing to incorporate a meticulously designed cutting strategy to reduce waste during construction can undermine the efficiency of cost optimization [4]. In the context of the solid waste stream, construction and demolition residues would comprise approximately 23% of the total volume. This translates to an annual production of over 100 million metric tonnes [5]. Similar waste proportions have been reported in various other nations, corroborating the United States' estimates. A notable portion of this waste results from inefficient material utilization, representing an avoidable fraction of waste generation [6]. Enhanced efficiency in material usage would consequently diminish the quantity of surplus materials, reduce unnecessary workmanship, and minimize the associated costs such as waste disposal and transportation fees. Certainly, effective resource utilization serves the greater global interest, extending beyond the immediate concerns of industrialists. Improper disposal of waste generated from stock-cutting operations can potentially contribute to environmental pollution, while unchecked wastefulness poses a significant risk to the exhaustion of our planet's invaluable resources [7]. Two different strategies exist for this problem: minimizing waste during fabrication or reusing materials from other structures.

While the former approach has not received great attention among experts in the civil engineering field, it serves as a central focus of this research. The latter option has been extensively explored by Brütting et al. [8], who advocate for a circular economy model to reduce costs and environmental impact in construction. In this study, the length and number of predefined stock elements obtained from a previous structure are the design variables of the optimization. Hence, the geometry and topology of the structure are predetermined by the mechanical and geometric properties of available elements.

A new Mixed-Integer Linear Programming (MILP) formulation for discrete sizing and topology optimization of truss structures has been also recently proposed performing significantly better than all other formulations [9,10]. In their scientific endeavours, Brütting et al. also introduced a method to enhance the configurational efficiency of stock or kit-of-parts, enabling the reusing of its constituent elements across multiple structural contexts. This strategic consideration led to the proliferation of reusability within a stock of items across various structures, consequently resulting in a further reduction of waste generation.

With the aim of minimizing waste, the Cutting Stock Problem (CSP) [11,12] is an essential research topic to focus on to reduce waste in the construction industry.

The innovative aspects introduced in the present study are focused on an optimization procedure aimed at minimizing structural waste, and to reduce the amount of material stock produced by the factory. This approach introduces a paradigm change considering constructability issues [13] as cutting patterns during the production phase, contrasting with the conventional minimum-weight optimization approach. The advantages of the adopted approach are expressed both in terms of mass savings (i.e. waste reduction) and Carbon footprint emission.

2. Structural Optimization Framework

When considering the cutting stock problem in the context of structural optimization, the goal is to design a structure that minimizes material usage while still satisfying the boundary conditions. This can be achieved by determining the optimal cross-section assignment of the items composing the stock which are used for the structure assembly. In the following sections, the formulation of the optimization problem has been introduced.

In the context of this study, a specific terminology is adopted defining the *member* a positional unit or *bar* within a reticulated structure, *member length* the distance between nodes at that specific position. On the other hand, referring to the requested stock, the terms *element* or *item* are also used to describe the individual constituent of a stock obtained after cutting procedures on the commercial piece, called *bin*, produced into the factory. It is worth noting that the *elements* or *items* obtained as cutting patterns coincide with the *members* or *bars* composing the structure.

2.1. Problem Statement Definition

With respect to traditional optimization approaches (i.e [14,15]) in which the Objective Function (OF) is expressed in terms of the total weight of the structure as a sum of the mass of each element (structural mass), in this study the target function, $W(x)$, has been evaluated by computing the amount of steel requested during the production phase (stock mass). The structural cost can be expressed in the following form:

$$W(\mathbf{x}) = \rho \sum_{g=1}^{g=k} n_g A_g(\mathbf{x}) L_g \tag{1}$$

where ρ is the steel mass density assumed to be equal for all members composing the structure. n_g, A_g and L_g are the cardinality, the cross-sectional area, and the length of bins belonging to the same group g of elements with the same cross-sectional area A_g, respectively. k represents the total number of groups of elements with the same cross-sectional areas which dynamically change according to the stock output.

The design variable vector, $\mathbf{x}$, represents the set of discrete cross-sectional areas of each element such that the bins area, A_g, can be evaluated. The length of this vector as well as the grouping strategy adopted to assign the same section to different members will be declared case-by-case.

The CSP routine has been implemented within the optimization process and it has been independently solved for all groups of elements with the same cross-sectional properties. Finally, the solutions obtained by the CSP routine, complying with the established structural constraints, have been adopted for the evaluation of the OF fitness (i.e. number of bins).

The optimum design problem, considered in the present work, is a constrained problem. It can be transformed into an unconstrained one using a penalty function. Here, a proper penalty function formulation has been adopted, so the OF of the problem can be computed as

$$min f(x) = W(x)\left[1 + C\left(\sum_{i=1}^{i=ne} v_i^s + \sum_{j=1}^{j=nj} v_j^d\right)\right] \tag{2}$$

subjected to:

$$V_i^t = \frac{N_{i,ED}}{N_{t,RD}} - 1.0 \quad i = 1, 2, ...ne \tag{3}$$

$$V_i^c = \frac{N_{i,ED}}{N_{c,RD}} - 1.0 \quad i = 1, 2, ...ne \tag{4}$$

$$V_i^b = \frac{N_{i,ED}}{N_{b,RD}} - 1.0 \quad i = 1, 2, ...ne \tag{5}$$

$$V_j^d = \frac{\delta_j}{\delta_{max,y}} - 1.0 \quad j = 1, 2, ...nj \tag{6}$$

where $N_{t,RD}$, $N_{c,RD}$, $N_{b,RD}$ are the tension strength, compression strength and buckling strength of the specific section calculated according to Eurocode 3 (EN 1993-1:2005 and EN 1993-2:2006) while N_{ED} represents the stress acting to the single member. δ and $\delta_{max,y}$ are the vertical displacement experienced by the j-th node and the maximum value assumed as threshold, respectively. The higher allowable displacement depends to the specific application and has been settled case-by-case.

In Eq.2, $W(x)$ is calculated by Eq.(1); C is a penalty constant, which is equal to 10 in this work; v_i^s, v_j^d, and v_i^p are the violations of normalized stress ratio, displacement ratio and size considerations, respectively and are computed using Eq.7.

$$\{v_i^s, v_j^d\} = max\left(0, \{V_i^t, V_i^c, V_i^b\}, V_j^d\right) \tag{7}$$

In this way, the penalty function integrates information related to either magnitude of penalization's level and number of unfeasible individuals.

3. Model definition and parameters' setting

In this section, the case study will be presented and details concerning the parameters' setting of the analysis will be introduced. The adopted reticular dome consists of 102 bars with varying lengths and inclinations, all interconnected by 43 spherical joints (see Fig. 1). Because of its high number of steel members, the investigated case study has been considered of particular interest to demonstrate the advantages of the proposed optimization framework. It is constrained by simple supports at each joint of the base.

To delve into more specific details, each level of the structure is comprised of circular horizontal hoops and diagonal bars. The first and second levels consist of 24 diagonal bars and 12 members composing each circular ring. Moving upwards, the third and fourth levels include 18 and 6 diagonal bars, respectively, interconnected by a horizontal hoop consisting of six bars.

In Fig. 1, a graphical representation of the main groups of elements composing the structure has been reported. As illustrated in previous works (e.g., [16,17]), the optimal grouping strategy operated by the optimizer has a crucial role in reducing computational effort and achieving the best cutting criteria for minimum waste.

The discrete design variables are determined by selecting among 150 Circular Hallow (CHS) cross-sectional areas from a standard list (EN 10210) complying with the identified grouping strategy. Hence, elements with similar structural behavior and belonging to the same cluster have the same cross-sections.

In the proposed approach, the structure experiences only gravitational actions like structural and non-structural permanent loads, snow and maintenance. Structural glass has been chosen as the skin area of the dome and a non-structural permanent load equal to 0.2 kN/m^2 has been adopted. According to European standard regulation, live loads like snow and maintenance have been assumed equal to 1.5 kN/m^2 and 0.5 kN/m^2, respectively. Consequently, all the loads have been applied at the level of the joints as concentrated loads according to the corresponding influence area.

Finally, in order to provide a comprehensive overview of the numerical model assumptions pertaining to the material properties and geometric characteristics of the truss as well as the parameters' setting of the analysis, Tables 1 and 2 have been reported, respectively.

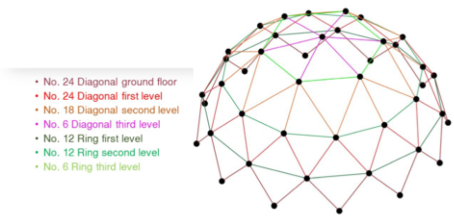


Figure 1. Type of elements composing the dome. Members with similar structural behavior are depicted with the same color.

Table 1. Optimization algorithm parameters set by the operator.

Parameter	Value
Maximum number of iterations	200
Number of individuals per population	200
Catalogue percentage of reduction	5%
Mutations' probability	1%
Proportional children	1 child for each parent
Stagnation condition	10 iterations

Table 2. Model assumption.

Parameter	**Value**
Modulus of elasticity of steel E	210000 MPa
Steel density ρ	7.85 t/m^3
Length of purchased bars (bins) L_{bin}	18 m
Number of design variables	7
Bounds of design variables (A_{min}, A_{max})	[137, 4000] mm^2

4. Outcomes of the Optimization analysis

The problem statement outlined in the section 2.1 serves as the basis for optimizing the dome. The comparison is based on two different optimization scenarios:

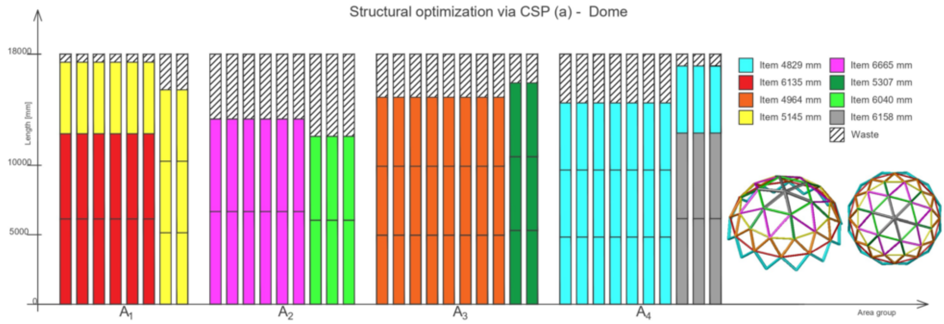
- **Scenario (a)**: SO implementing CSP for the minimization of purchased steel bars where the OF is expressed by Eq. 2;
- **Scenario (b)**: SO by adopting a traditional minimum-weight approach where the OF to be minimized is the mass of the structure.

In this way, the optimal design obtained from the two distinct approaches can be compared in terms of i) *Structural weight* (i.e. total mass), M_{truss}, ii) *stock mass*, M_{stock}, and iii) *Waste mass*, M_{waste}. The outcomes of the optimization process are reported in table 3.

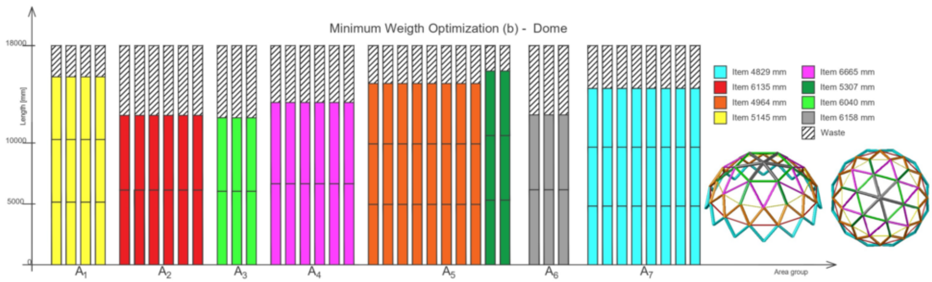
Table 3. Outputs of the optimization process obtained from scenario (a) and scenario (b).

	M_{truss} [kg]	M_{stock} [kg]	M_{waste} [kg]	M_{waste}/M_{truss}	M_{waste}/M_{stock}
Scenario (a)	2851.1	3329.7	478.4	16.0 %	14.0 %
Scenario (b)	2773.6	3683.2	909.5	32.8 %	24.7 %

As expected, scenario (b) leads to a mass saving of the M_{truss} with respect to scenario (a) even if the M_{stock} of the former still remains significantly high. Specifically, for scenario (b), the M_{truss} is equal to 75% of the M_{stock} resulting in a significant waste equal to 30% of the M_{truss}. In other words, for the realization of the dome, the total waste is almost 1/3 the mass of the dome. On the other hand, an evident improvement has been obtained following the CSP approach. Scenario (a) leads to a significant reduction of the waste equal to only 16.0% of the mass of the dome. Examining Figure 2(a)-(b), it becomes clear that the benefits of implementing the proposed approach are evident in terms of material saving. The optimal design of the dome, achieved through a straightforward weight minimization process (scenario b), leads to substantial material wastage, as evidenced by the non-optimal cutting pattern of components. Coherently, as observed numerically, the total M_{stock} obtained by scenario (b) is significantly higher than one from scenario (a). As for the previous case study, the optimal stock of elements has been achieved by an optimized grouping strategy adopted by the optimizer. In scenario (b), the optimizer selects 7 distinct cross-sectional areas to enhance the structural performance of each group element to achieve the minimum weight of the structure. In contrast, in scenario (a), where the CSP is resolved during each iteration of the optimization procedure, the total number of bins required during production is significantly reduced, and the variety of different cross-sections decreases to 4.



(a)



(b)

Figure 2. Optimal cutting pattern obtained by (a) the CSP approach and (b) the minimum-weight approach for the trussed dome.

The impact of integrating CSP with structural optimization becomes clearer when comparing the total number of bins obtained in both scenarios. Despite scenario (b) resulting in a lower structural mass compared to scenario (a), the reduction in material wastage, derived from the CSP approach, overcomes the weight loss.

5. Environmental analysis

To verify the environmental performance of the solutions obtained through the two different optimization approaches, a Life Cycle Assessment (LCA) [18,19] is performed according to ISO 14040 - 14044. Since the analysis is mainly targeted at producers, the production stage is considered along with the prefabrication process. This means that the analysis aims to assess the impact of raw material extraction, transport to the manufacturing location, manufacturing and stock steel profiles, and final (laser) cutting before transport to the construction site (A1-A3, according to EN 15798). Global Warming Potential (GWP 100 years) is the considered impact indicator, as defined in EN 15804+A2. The selected functional unit, F.U. is the *steel profile length leaving from the stock*, expressed in meter [m]. Environmental information is selected from generic datasets for steel profile (low scrap steel, source ÖKOBAUDAT) and a specific model for laser cutting. A1-A3 module impacts also entail scrap material of the final cutting, which will not be sent to the construction site. The end-of-life of scrap steel profiles is not accounted for since they belong to a different system lifecycle and, therefore, are out of scope.

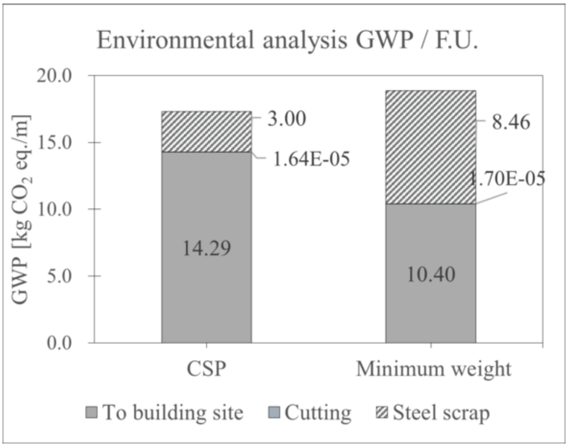


Figure 3. LCA results. Global warming potential [kg CO_2/m].

Figure 3 shows the results of LCA analyses in [kg CO_2 eq./m]. Regarding impact per F.U., there is a slight difference between the two approaches, where the CSP approach presents lower values. Furthermore, it can be noticed that the CSP approach has significant advantages in both reducing scrap steel sections and in terms of process efficiency. 83% of the produced impact is attributable to steel profiles being transported to a construction site, which, therefore, become part of a building system. In the case of the minimum weight approach, 45% of the impact is allocated to scrap steel sections that will be re-processed for recycling or, only if possible, in the best case, re-used to derive further steel sections. It can be finally noticed that the cutting process does not significantly affect the total impact. Slightly higher values are recorded for the minimum-weight approach, as expected, due to a higher number of profile cuttings. The relatively low impacts can be due to the specific selected process model and the energy required for the cutting process, which is lower than the manufacturing of stock steel profiles.

Overall, the CSP approach's higher efficiency and environmental advantages are demonstrated compared to the minimum weight.

6. Conclusions and Future Developments

In this paper, the potential of a new optimization approach based on the CSP routine is proposed. Results show the advantages of adopting the current approach against the traditional minimum-weight approach. Mass saving and a significant GWP reduction obtained by the former are observed. Specifically, the steel waste is reduced from almost 1 ton obtained from scenario b up to 0.5 tons from scenario a. On the other hand, Life-Cycle analysis shows no significant differences among the investigated scenarios, however, it is worth noting that the amount of GWP deriving from the waste is reduced to half when moving from the traditional minimum-weight approach to the CSP approach. In future developments, the proposed approach will be applied to minimize the amount of commercial steel required investigating the effect of the number of members composing the structure on the optimal cutting patterns and expanding the current optimization framework to different case studies like tall buildings and bridges.

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