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Construction-based optimization criteria for steel trusses

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Abstract

In this study, a grouping strategy for the simultaneous size, shape and topology optimization of steel truss structures has been presented. The novelty of our study relies in the definition of the objective function, not intended to a simple weight minimization, but accounting also for constructability issues. More precisely, based on practical and cost considerations, the optimum number of distinct cross-sections used has been sought. The considered numerical example has been illustrated, i.e., the one related to the simple truss. Also, the dynamic grouping strategy, as well as the assembly of the model have been illustrated. The objective function formulation has been finally proposed, with the careful calibration of all the parameters involved. The parametric modelling, the FEM structural analysis and the optimization have been carried out with Rhinoceros plug-ins, Grasshopper, Karamba3D and Octopus, respectively. The performance of the proposed objective function has been examined in different conditions, with simultaneous size, shape and topology optimization cases. Results have been reported, where the influence of each penalty function has been studied and analyzed with great detail.

Keywords: constructability, size optimization, shape optimization, topology optimization, penalty function, truss analysis.

1 Introduction

According to the constructability task force of the Construction Industry Institute (CII), which is based at the University of Texas and was established in 1986, constructability refers to the optimal utilization of construction knowledge and experience in various stages of a project, such as planning, design, procurement, and field operations, in order to attain the project's overall objectives. In the United Kingdom, "buildability" is a term that has been employed to describe the degree to which a building's design makes construction easy, while still satisfying the building's overall requirements. However, in this current work, the definition which was provided by Anderson et al.[1] is considered, which emphasizes the integration of construction knowledge, resources, technology, and experience into the engineering and design of a project.

The key aspect one should have in mind is that information and experience gained throughout the construction phase must be accounted for and shared in the design in order to improve project objectives. Aimed at accomplishing this task, several considerations can be made, ranging from general management organization recommendations to more particular techniques. O'Connor et al. [2] started from CII definition and explored seven concepts for improving constructability. Pulaski and Horman [3], proposed a model to organize constructability information for design, according to timing and levels of detail. Constructability considerations provide several important advantages, many of which are sometimes challenging to understand and evaluate. Russell et al.[4] distinguished such benefits between qualitative and quantitative ones.

Since it is crucial that any construction project is carried out by the planned completion date, to reduce issues like scheduling conflicts, delays and disagreements that may arise, Arditi et al.[5] conducted a questionnaire survey of design companies about the adoption of constructability. Another important aspect, emphasized in the work of Ruby [6] is the fact that constructability is a design philosophy that originates from the conceptual design stage, continues through design, and links project planning with design and construction. As stated by Khan [7], making use of construction knowledge from the earliest stages of a project, where the ability to influence cost is at greatest, makes sense from both practical and financial viewpoints. Paulson [8] described the interrelationships between engineering design, construction and operation costs for a facility, showing how the level of control on those costs decreases as the project evolves. In general, using standardized components and systems can help improve constructability by reducing the need for custom fabrication and assembly. The idea of standardization has been defined, by Pasquire and Gibb [9] as the widespread adoption of consistent components, methods, or processes that have a track record of success and are repeatedly used with regularity.

Standardization is a term that can include different meanings, from the employment of standard elements in the design of a structure, avoiding particular and unique shapes or sections, but also the repetition of members, connections, as well as procedures in the overall project. Furthermore, from a more general point of view, standardization is also paired with modularization and pre-assemble techniques. By looking at the design of a simple truss structure, the structural choices that can be made with a standardization-driven orientation regard the employment of the least amount of different cross-sections, but also the reduction in variation of the connections. In any case, the verification of structural and geometric requirements should be always considered.

From the experience of previous studies, it can be understood how integrating constructability considerations in the design phase can compete with the typical goal of minimizing weight. For example, the complexity topic that affects truss structures involves reducing the number of nodes, which in turn leads to longer members. In turn, these elements would have bigger sections to satisfy structural requirements, perhaps implying heavier designs. The same implication would follow the standardization technique, which encourages less diversity in the sections used. However, repetition of members sizes at the cost of some added member weight, can simplifies detailing, fabrication and erection costs. Thus, a simpler and standardized design can help reduce the overall cost, which is typically the most appealing objective.

Therefore, constructability in structural optimization can be interpreted as the process of incorporating construction expertise and knowledge into the design and optimization phase. The difficulty of such process is that there are many factors involved. Many of these influencing factors regard the management procedure, thus a good collaboration between all the team members, as well as the importance of having professional and qualified personnel, early involvement of contractor in design and so on. However, the present study is more focused on examining the constructability factors that can be integrated into structural design decisions, particularly within the optimization framework.

2 Methods

An optimization problem starts with the definition of three main components, namely the Objective Function (OF), the design variables and the constraints. The former one, also called Merit Function, is the quantity that is going to be minimized or maximized by changing the set of design variables. During the procedure, the structure under study has to satisfy some constraints which in general are referred to stresses, displacements, natural frequencies or geometric requirements. They can be in the form of inequalities or equalities, however generally the second ones are converted into the other formulation by means of a tolerance value. For example, $h(X) = 0$ can be transformed in $|h(X)| \leq \varepsilon$, where ε is the small tolerance allowed.

In addition, constraints could be combined into the objective function as penalty functions to convert the constrained problem to an unconstrained one. The optimizations, based on the nature of the decision variables, can be classified into discrete or continuous problems. The values of continuous design variables fluctuate within a certain range, while discrete ones can assume only certain values in a finite set of available candidates. When possible, discrete problems are treated as continuous ones and only at the end round-off procedure is performed. The range of design variables is called search space or design space, which could be further divided into feasible and infeasible domains. Therefore, the constraints are limiting the design space, with the so-called "constraint surface". Nevertheless, not all of them contribute to the surface definition, thus they will be divided into active and inactive ones. The general formulation of the optimization can be written as follows:

$$Min\ or\ Max: f(\boldsymbol{X}) \tag{1.a}$$

$$Subjected\ to: \ g_i(\boldsymbol{X}) \leq 0, \qquad i = \ 1, 2, 3 \ldots m \tag{1.b}$$

$$h_j(\boldsymbol{X}) = 0, \ j = \ 1, 2, 3 \ldots p \tag{1.c}$$

$$\boldsymbol{X} \in \ S \tag{1.d}$$

where $\boldsymbol{X}$ is the vector of the n design variable $\boldsymbol{X} = \{x_1, x_2, \ldots x_n\}$; $f(\boldsymbol{X})$ is the objective function and $g_i(\boldsymbol{X})\ and\ h_j(\boldsymbol{X})$ are the m inequalities and p equality constrains, respectively; and S is the search space of the optimization problem.

3 Size, shape and topology optimization of steel trussed beam

In the current work, the authors are going to describe focus of the study. Specifically, we have performed the simultaneous size, shape and topology optimization of steel truss structures, not intended to the most common weight minimization, but developing a new objective function integrated with constructability criteria. At first, we have introduced the truss structure characteristics and employments in civil engineering, as well as how they can be modelled following a parametric design; then we have clarified the design variables considered in the optimization, along with the grouping strategy developed to improve the schematization of the problem. Subsequently the model set-up, the definition of the Objective Function has been discussed, starting from the original hypothesis considered to the final formulation.. In particular, in this section we have depicted the analysis at the truss level, with the intent to enlarge the point of view towards the scale of a single storey industrial building.

The software used in this work to exploit the parametric design principles is Rhinoceros 3D, which includes Grasshopper 3D with Karamba 3D and Octopus plug-ins. In order to start the optimization, the algorithm needs to be connected to the different design variables previously defined and to the objective function that needs to be minimized. Therefore, the geometry of our structure has been parametrically modelled in Grasshopper. Then, it has been traduced in the FEM elements using the Karamba3D components, assigning the cross-sections, loads and supports. Finally, the design variables and the objective function have been connected to the Octopus optimizator. As stated before, our intent is to perform a simultaneous size, shape and topology optimization of a steel truss structure. A truss structure with total span length of 20 meters is considered in this paper, it was modelled parametrically by creating one half of the geometry and utilizing its symmetry with respect to the vertical axis in the middle as it is shown in Figure 2.

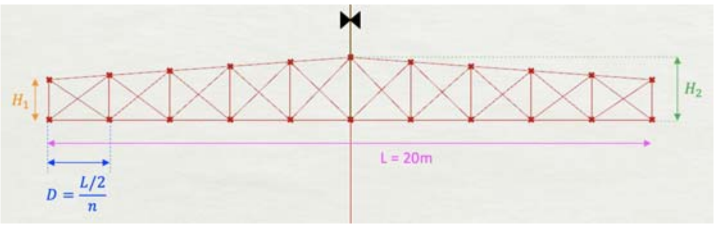

Figure 2: Schematic representation of the truss

The shape optimization variables have been identified as the number of subdivisions of half the chords (n), along with the heights of the edges (H_1) and middle point (H_2) of the upper chord. Always considering half geometry, the range in which n can be varied is between 3 and 10. The upper bound has been set considering a minimum distance between consecutive nodes of 1.00 meter, while the lower bound accounting for the grouping strategy, explained in the next paragraph. A height range for the edges H_1 was established through a pre-dimensioning of the structure in between a value of $L/15$ and $L/10$, while the central height H_2 ranges between the current value of H_1 and a maximum of $L/8$.

These variables are not independent one from each other because of geometrical considerations. In fact, the inclination of diagonal members is suggested to be between 30° and 60° degrees. Figure 3 represents the relationship between H_1 and H_2 and it was established as a function of n by combining two conditions:

- Pre-dimensioning rules

$$\frac{L}{15} < H_1 < \frac{L}{10} \tag{2}$$

$$H_1 < H_2 < \frac{L}{8} \tag{3}$$

- Diagonals inclination in between 30° and 60°

$$D \cdot tan30° < H_i < D \tag{4}$$

with D equal to the distance between consecutive nodes, computed as $\frac{L/2}{n}$.

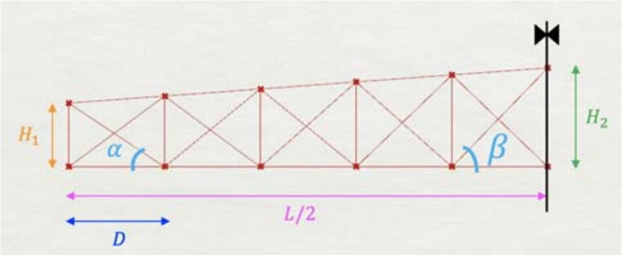

Figure 3: Scheme for relationship between n and H_1, H_2, where α should be at least 30°and β maximum value is 60°

Regarding the topology optimization, five different types of trusses, namely Vierendeel, Brown, Pratt, Howe, and Warren, were created in Grasshopper. In particular, to switch from one configuration to the other in our optimization, a slider ranging from 0 to 4 was created, in which each number represent a truss type. For example, 0 stands for the Vierendeel one, thus if the topology design variable for the current individual is at 0 value, the configuration analyzed is the Vierendeel one.

Finally, the size optimization has been carried out by varying the cross-sections of the truss's members. Specifically, CHS (circular hollow sections) profiles were assigned. In Karamba3D there is a pre-defined catalogue, which has been limited to the first 100 values in order to reduce the computational effort of the optimizer. This reduction has been computed by following the Eurocode 3 [10] specification, in which the general formulation regarding the stability of truss's members can be written as: $N_{Rd} = \frac{A \cdot fy}{\gamma_m}$. Actually it should be distinguished for tension or compression members, as well as for the different classes of cross-sections, but this was just a preliminary, rough and simplified evaluation. The procedure which is followed to assemble the model is represented in Figure 4.

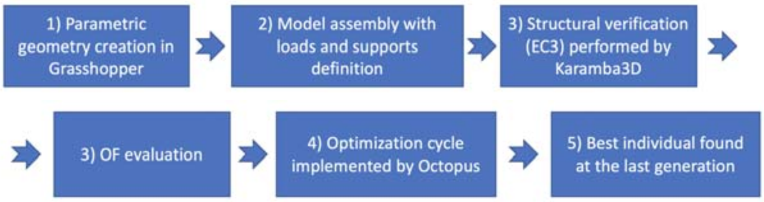

Figure 4: Basic procedure flow

After assembling the model, the solver will conduct structural analyses for each configuration, and the Objective Function can be implemented from the obtained output. In particular, its formulation will be discussed later, however here the aim is just to summarize the basic flow of our analysis. It must be highlighted the fact that Octopus optimizer works by setting the population size and the number of generations, thus once the optimization has reached the last individual of the last generation it will stop. During each generation, the individuals are created by changing the design variables and imposing the structural verifications according to the Eurocode 3 [10], until the best configuration is obtained. In Figure 5, a schematic flow chart of our procedure is reported. Specifically, (It) stands for iteration number, while at STEP 0 the input assumptions regard the fixed 20 m length of the truss, the number of groups equal to 3 and the setting of total number of iterations It_{max} and population size.

As mentioned previously, the optimization is not solely focused on weight minimization but also incorporates structural verifications and constructability considerations. To properly formulate the problem, three primary components of the optimization, namely the objective function, design variables, and applied constraints, must be defined. The optimization formulation is expressed as follows:

$$Min\ F(\boldsymbol{x}) = \rho \sum_{i=1}^{N} (A_i . l_i) . \phi_1(n_{un}) . \phi_2(N_a) . \phi_3(n) \tag{5.a}$$

Subjected to:

$$\frac{N_{Ed}}{N_{Rd}} \leq 1 \tag{5.b}$$

$$x_{i,min} < x_i < x_{i,max} \tag{5.c}$$

where N is the total number of elements in the truss and x_i is the vector of design variables.

In equation (5.a), the penalties are respectively:

$$\phi_1 = (1 + K_1 . n_{un}) \tag{6}$$

$$\phi_2 = (1 + \Delta) - e^{-\beta .(N_a - \frac{ln\Delta}{\beta})} \tag{7}$$

$$\phi_3 = (1 + \gamma) - e^{-\alpha .(n - \frac{ln\gamma}{\alpha})} \tag{8}$$

All the parameters related to the penalty functions have been calibrated by means of the analysis reported in the next subsections; their resulting values are summarized in Table 1.

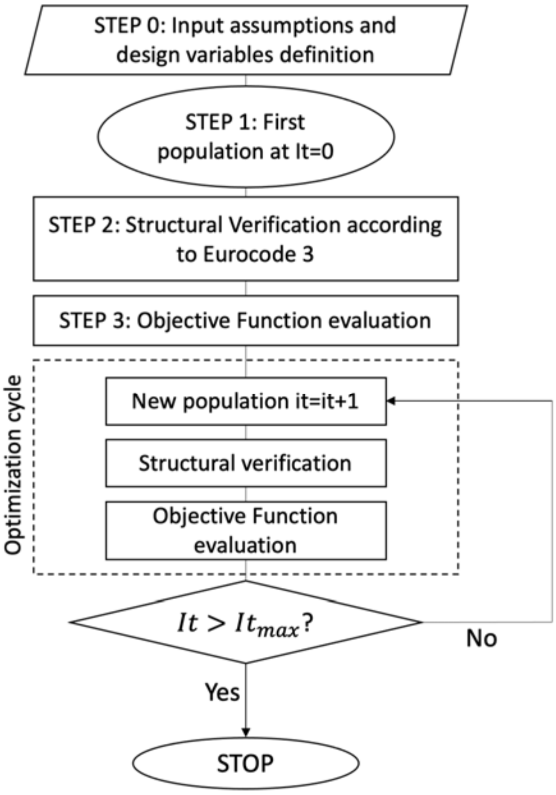

Figure 5: Flow chart

Parameter	Value
K_1	10
Δ	2.70
β	0.1
γ	1.157
α	0.1

Table 1: Penalties parameters

With the first penalty, a constraint referred to element buckling verification is implemented, which is proportional to the number of elements in the unfeasible region, n_{un}, and amplified by a coefficient K_1. Instead, ϕ_2 and ϕ_3, are introducing constructability criteria that, once more, encourage the optimization towards heavier designs. In particular, ϕ_2 is limiting the number of distinct cross-sections used to construct the entire truss (N_a). On the other hand, ϕ_3 tries to reduce the design complexity by lowering the number of subdivisions of the truss, thus the overall number of pieces to be assembled.

3 Results

The resulting best individual found by Octopus is represented in Figure 6.

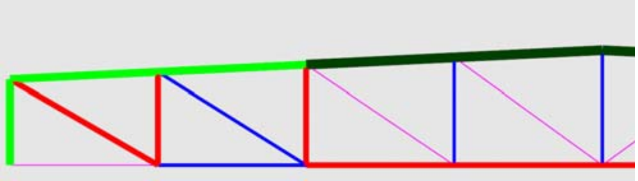

Figure 6: Configuration of the optimized truss

Table 2 summarized the cross-sections used in the specific truss, while in Table 3 shows its main characteristics.

	CHS 1°group (mm)	**CHS 2°group (mm)**	**CHS 3°group (mm)**
Lower Chord	101.6 × 2	60.3 × 2	21.3 × 2
Upper Chord + Ext. Vert. Structs	168.3 × 3	139.7 × 3	139.7 × 3
Int. Vert. Structs	60.3 × 2	101.6 × 2	101.6 × 2
Downward-Upward Diagonals	21.3 × 2	60.3 × 2	101.6 × 2

Table 2: Cross-sections of the optimized truss

Best OF	**Weight [kN]**	N_a	n	H_1	H_2	n_1	n_2	n_3
12.4295	4.3627	5	4	1.7	2.38	1	1	2

Table 3: Main features of the optimized truss

Figures from 7 to 12 represent the charts about the best individual found at each iteration, as well as its weight, number of sections used and the unfeasibility proportion throughout the optimization.

CHS cross-sections are assigned to each element as it can be noted From Table 2. Also, in this case a balance between complexity and weight of the truss structure has been found, as can be observed from Table 3. However, the most important consideration that can be drawn from the results refers to the topology selected by the optimizer, which is Pratt one. As a matter of fact, it should be expected due to the fact that only gravitational loadings were considered. In Pratt trusses, as explained earlier, the diagonal members, which are the longest ones, are in tension and not in compression, thus they will not require additional by buckling instability verifications

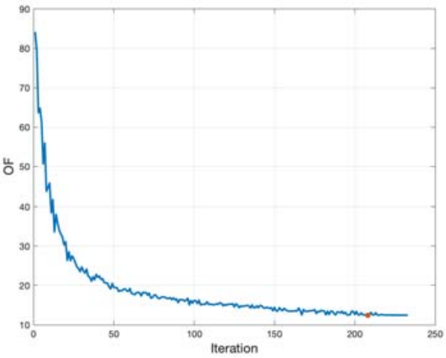

Figure 7: Best individual - Iteration

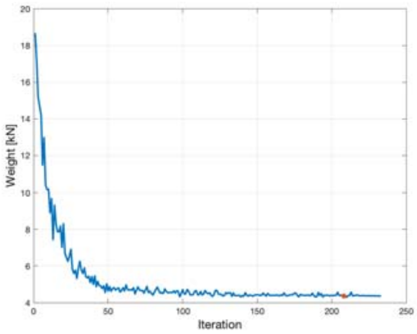

Figure 8: Weight of best individual at each iteration

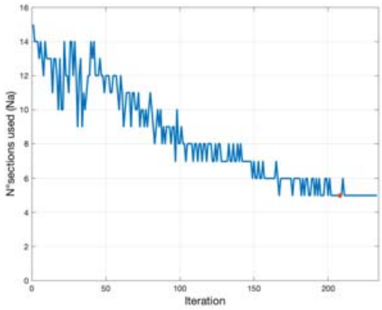

Figure 9: N_a of best individual at each iteration

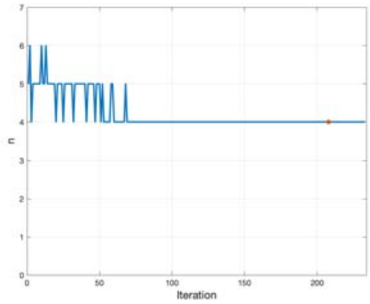

Figure 10: n of best individual at each iteration

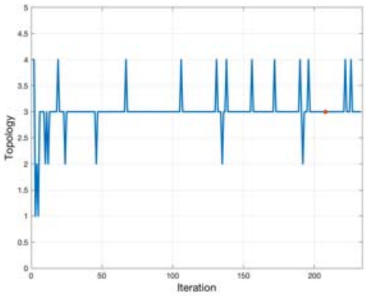

Figure 11: Topology of best individual at each iteration

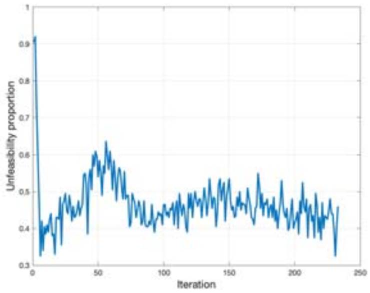

Figure 12: Unfeasibility proportion

4 Conclusions and Contributions

In this study, the applicability of the proposed objective function was considered for truss structures. It has been stresses the importance of constructability considerations together with a weight minimization, aimed at finding a simplified and standardized design. By applying simultaneous size, shape and topology optimization, a consideration of three penalty functions, how they work and how they can be calibrated according to the specific needs. Moreover, for what regard the case in which the topology slider has been considered as design variable too, the Pratt configuration has been chosen. This was, once again, expected because, for gravitational loads only, in this type of truss the longer diagonal elements work in tension, thus avoiding further verifications for compressive states. On the contrary, in the Howe truss, for example, the diagonals are in compression thus it should be avoided. The most challenging task was to understand the calibration of the parameters employed in each single penalty. Specific trends have been identified and recommendations on possible changes have been provided. Another significant finding from the analyses is that the algorithm is not sufficiently guided in the topology identification. In fact, in our optimization, Octopus is free to assign any possible type of configuration, without a specific encouragement towards a specific one. Most of the time, it is able to retrieve the one that reduces the number of pieces, that in turn abate the OF value, however there could be a more stable trend. Therefore, introducing a gradual exploration in the algorithm could be considered. Specifically, it should be improved at the beginning in order to find the best one, and then reduced to lessen the computational effort. Another future investigation could be the optimization of the cross-section's profiles, thus obtaining the best one for each specific component. In fact, it is known that for the truss elements it could be convenient to employ I-shaped or H-shaped profiles, as well as UPN or L-shaped ones. In any case, the optimization of the profiles should be aimed at finding feasible connections between the components. Furthermore, expanding the analysis considering other load combinations is suggested. The limit imposed by Karamba3D of a single load combination can be overcomed in different ways. In Grasshopper environment there are plug-ins that allow to solve the structural analysis using external solutors, like SAP2000. In this way, multiple load combinations can be taken into account. The main drawback in such procedure would be the increase of the computational time, however it would result in a more comprehensive analysis.

Acknowledgements

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