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Integration of Life Cycle Assessment in Structural Optimisation of Steel Structures

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Abstract

Lowering environmental impacts has lately been a critical objective of structural optimisation due to the significant amount of greenhouse gas emissions in the civil engineering sector.

This work introduces a Life Cycle Assessment based multi-objective optimisation framework for the optimal design of mixed steel-timber structures by varying the building design's size, shape, and topology. The study's novelty stems from the integration of an environmental objective function in the early design process, based on Life Cycle Assessment methodology and standard environmental indicators, and the definition of a structural target function where a penalty-based approach is implemented for reducing structural complexity in situ. The structural cost and the Global Warming Potential are the objective functions of the optimisation problem. The analysis outcomes show a mass-saving of almost 20% and a significant reduction of Global

Warming Potential emissions equal to 50% when steel-timber mixed designs are preferred to steel-only configurations.

Keywords: life-cycle-assessment, multi-criteria, steel, constructability, truss, structural optimization.

1 Introduction

Lowering environmental impacts has been a key objective in structural optimisation due to the significant amount of greenhouse gas (GHG) emissions in the civil engineering sector and the increasing attention on environmental concerns [1]. To promote environmental quality, it is especially critical for planers to identify strategies for the reduction of embodied impacts in the early design stages, where the most significant improvement lies [2].

In structural planning, environmental and economic objective functions have been commonly combined within multi-criteria approaches [3, 4] because of the similar trend of these target functions. One of the most applied strategies for improving the cost and environmental performance of construction systems is the optimised use of raw materials through the reduction of the structural cost (i.e. weight) for the construction of different RC structures (Kaveh et al. [5], Camp et al. [6], Park et al. [7] and Santoro et al. [8]). In the beginning, researchers and practitioners focused on theoretical applications mainly referred to reinforced concrete (e.g., [9, 10]) or steel-concrete composite elements [11, 12] aiming to reduce the amount of steel reinforcement [13]. In this context, Paya et al. in [14] and [15] investigated the optimal design of reinforced concrete (RC) building frames based on a multiobjective Simulated Annealing (MOSA).

Even if steel constructions are the most widely employed, few works in the literature focus on reducing their embodied emissions by simultaneously addressing the constructability aspect. As observed by several authors [16, 17], the constructability aspects are mainly related to reducing the structural complexity during the construction process, resulting in significant time-work savings and a drastic simplification of the production, assembly and erection activities, in situ. Galante et al. in [18] and Greiner et al. in [19] stressed the importance of reducing different numbers of sections to efficiently manage practical issues during several phases of the construction process. In this sense, a multicriteria design approach based on the minimisation of material cost, material weight, number of different transversal sections and perimeter of the elements for the reduction of the maintenance cost was proposed by Sarma and Adeli in [20, 21]. The same authors in [22] address the life-cycle cost optimisation of steel structures by considering life cycle, initial and annual maintenance, inspection, repair, operating, probable failure, and dismantling costs.

The lack of well-established multiobjective optimisation frameworks to investigate the constructability-environmental combined effects on truss steel structures contrasts with the outcomes of recent studies.

However, even if constructability aspects in steel structures represent a crucial topic that deserves more attention, several researchers focused on the potential environmental impact of optimised steel [23] and/or mixed steel-concrete structures [24]. A crucial aspect that is drawing the attention of researchers is the embodied (also called grey) energy and impacts of buildings related to industrial processes for production, transportation assembly, and end-of-life [25].

In the last decades, Life Cycle Analyses have mainly been applied as powerful instruments to assess the sustainability of various types of structures and to provide an evaluation of building systems in a holistic perspective [26], allowing for the assessment of environmental, economic and social quality aspects. With the help of such tools, Ramon et al. [27] showed the advantages of adopting mixed (i.e., steel-timber) systems. With regard to the assessment of environmental quality, most studies and building environmental certification systems integrate life cycle analyses and evaluate Carbon Footprint (CF) [28] or Global Warming Potential (GWP) as a main environmental indicator.

While the integration of LCA within automatic routines for the optimal design of RC buildings is quite common in literature, few works mainly devoted to the assessment of optimal design for steel structures by involving environmental quality objectives can be recognised [29,30] and [31]. Innovative mathematical formulations of optimisation processes trading off environmental quality objectives with constructability criteria are needed and deemed vital in bridging the gap between theory and practice.

This work introduces an innovative LCA-based multiobjective optimisation framework for the preliminary design of 3D truss structures where lifecycle embodied impacts and structural aspects are investigated simultaneously.

2 Case Study: 3D Truss Roof of an Industrial Building

This section analyses the application case study of this work, and a novel multi-objective optimisation framework subjected to multi-criteria conditions is defined to identify the optimal design for reducing structural complexity and satisfying sustainability goals. Life Cycle Assessment (LCA) analyses are integrated into optimisation to achieve better environmental profiles in terms of GHG emissions.

The software implementation of the proposed methodology includes the interaction among (i) Rhinoceros, (ii) Grasshopper for parametric design and algorithms' generation, (iii) Karamba for Finite Element Analyses (FEA) of structural configurations, (iv) Octopus as a Multiobjective Optimiser (MOO) and (v) Lunchbox tool for integration of LCA analyses. Programming code like *Python* is adopted for the parametric modelling and the implementation of specific structural verifications toward the programming component already implemented in Grasshopper. The optimisation processes were run on a workstation DELL - Precision 7680 with an Intel Core i7 5,3 GHz processor with 32 GB RAM under the Microsoft Windows 11 operating system. The computational time for each is about 21600 s.

2.1 Parametric modelling and load definition

The potential of the parametric design is used herein to generate the structure's geometry. The structure is composed by a spatial reticular system realised by a series of aligned *semi-octahedral* modules with *tetrahedrons* interposed (see Fig.1) The double-layered space frame roof modules are obtained by adopting a certain number of repetitions with proper spacing in both x and y directions. This spacing acts as a variable of the problem by managing the number of connections. By increasing the number of the roof modules resulting in an increasing number of truss elements, the overall number of connections increases.

The structure's overall footprint is fixed at 60 meters in the x direction and 30 meters in the y direction, allowing for tighter or wider modules. Specifically, the roofing system components are classified as upper chord, lower chord, and diagonals. In addition, columns are introduced here with a height of 8 meters. All the assumed hypotheses aim to reproduce a typical industrial building design.

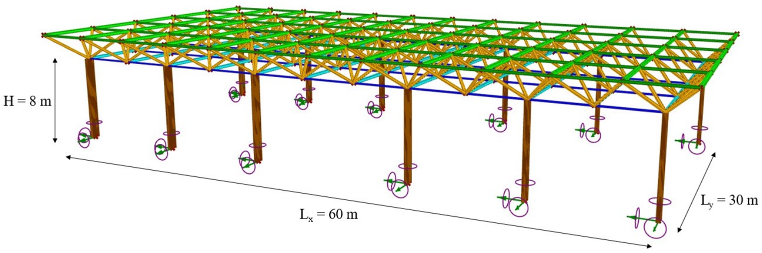

Figure 1: Industrial building parametric scheme

According to common practice, columns have been connected to the lower chord at the level of the bottom layer spherical connections. The row is mirrored on the other side in relation to an XZ plane located at $\frac{L_y}{2}$.

The spacing of these elements is parametrically determined. Due to the geometric configuration of the space truss, it is not easy to use an identifiable symmetry to reflect the components along the considered axis. Columns position are free to move along the perimeter of the building consistently with the number of divisions chosen by the optimiser. Then, fixed supports are positioned at the feet of each column.

Aiming to identify the optimal design of the investigated case study, the optimiser can select the best material between glued laminated timber (also called glulam) and steel grade S355. With specific regard to steel elements, the optimiser is allowed to assign open or closed sections.

A standard list of 170 different S355 steel sections according to European regulation EN 1993-1-1 and a list of 31 different rectangular glulam sections are adopted.

The CHS (closed section) or IPE sections (open section) could be potentially assigned to all the members composing upper and bottom chords and CHS or double-L sections for diagonals. Only rectangular glulam sections could be adopted for the columns' design. The optimiser could also prefer glulam solid rectangular sections for all the elements composing the roof.

The reason for this choice resides in the significant difference in CO_2 eq. derived from the two different materials, the class of sections, and their structural performances.

It is fascinating to compare steel with glulam since they may both be employed in the same kind of load-bearing systems. Compared to glulam, steel is more homogeneous and robust, allowing for the creation of thinner and slender structures. Steel, however, has far more production-related GHG emissions than timber. For instance, the former has a production phase GWP approximately twice that of the latter (based on Ökobaudat datasets).

The Ultimate Limit State (ULS) load combination is considered for static analysis subjected to the permanent structural (G_1) and non-structural load (G_2), maintenance (q_k) and snow (q_s) accounting for the gravitational load pattern according to the European and Italian code action definition. Wind load is considered as the only horizontal action acting on the structure.

In Tab. 1, an overview of the adopted actions for the evaluation of the critical combination and the corresponding amplification factor, γ, suggested by the Italian regulations, is reported:

Table 1: Summary of loads applied to the building and their relative value and coefficient

Load Type	**Load Name**	**Load Value** [KN/m^2]	γ	ψ
Dead Load	G_1	Structure weight	1.3	-
Perm. Non-struct. Load	G2	0.05	1.5	-
Maintenance Load	q_k	0.5	1.5	-
Snow Load	q_s	1.23	1.5	0.5
Wind Load	p	Depends on c_p and c_e	1.5	0.6

3 Multi-Objectives optimisation framework

The optimisation framework subjected to multi-criteria constraints for the industrial building application is herein described. Additionally, in order to carry out a multi-objective optimisation that fully utilises the capabilities of the Octopus optimiser, the environmental objective function formulation has been introduced. In this way, a range of equally optimal trade-off solutions will be obtained.

The first step is the definition of the relevant design variables (DVs). Aiming to assess the optimal sizing and shape of the structure the following DVs are adopted:

- Height of the roofing structure ranging from 1 to 4 m;

- Number of divisions in x direction ranging from 6 to 40;
- Number of divisions in y direction ranging from 3 to 20;
- Section for the upper chord and lower chord along X and Y directions, diagonals selection based on the 170 different steel open (double-L profile) and closed (CHS) cross sections or 31 Glulam solid rectangular catalogue;
- Section assigned to the columns based on the 150 different Glulam solid rectangular sections of the catalogue;

Once the DVs definition is established, space frame optimisation, which entails the modules of the industrial building (i.e. roof truss system and corresponding vertical supports), is done simultaneously concerning size, shape, and topology.

The mathematical formulation of the OF_1 can be expressed in the following form:

$$min f(\mathbf{x})_1 = \overbrace{\sum_{i=1}^{N} \rho_i A_i l_i \cdot \phi_1 \cdot \phi_3}^{\text{Elements}} + \overbrace{M_{node} \cdot \phi_2}^{\text{Connections}} \quad [ton] \tag{1}$$

subjected to structural verification for steel cross-sections according to the European Standard Regulation EC3 6.3.3(4)-6.61

$$V_i = \frac{N_{ED} \cdot \gamma_{M1}}{\chi_y \cdot N_{RD}} + k_{yy} \cdot \frac{M_{y,ED} \cdot \gamma_{M1}}{\chi_{LT} \cdot M_{y,RD}} + \frac{M_{z,ED} \cdot \gamma_{M1}}{M_{z,RD}} \leq 1.0 \quad i = 1,2,...ne \tag{2}$$

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

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

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

and glulam members following EN1995-1-6.3.2

$$\frac{\sigma_{c,0,d}}{k_{c,y} \cdot f_{c,0,d}} + k_m \cdot \frac{\sigma_{c,0,d}}{f_{m,y,d}} + \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1 \quad \textbf{or} \quad \frac{\sigma_{c,0,d}}{k_{c,y} \cdot f_{c,0,d}} + \frac{\sigma_{c,0,d}}{f_{m,y,d}} + k_m \cdot \frac{\sigma_{m,z,d}}{f_{m,z,d}} \tag{6}$$

for the elements subjected to combined axial compression-bending stress, accounting stability check, and the following verifications

$$\frac{\sigma_{t,0,d}}{f_{t,0,d}} \leq 1 \tag{7}$$

$$\frac{\sigma_{c,0,d}}{f_{c,0,d}} \leq 1 \quad \textbf{or} \quad \frac{\sigma_{c,90,d}}{k_{c,90} \cdot f_{c,90,d}} \leq 1 \tag{8}$$

for the truss elements subjected to tension parallel and perpendicular to the grain (see Eq. 7) and compression parallel and perpendicular to the grain (see Eq. 8)

Additionally, serviceability constraints are taken from NTC2018 and EN 1995-1-7.2

$$\begin{aligned} \delta_{max} &\leq \frac{L}{200} \quad for\, steel\, elements \\ \delta_{max} &\leq \frac{L}{150}\, to\, \frac{L}{300} \quad for\, timber\, elements \end{aligned} \tag{9}$$

have been involved within boundaries.

The proposed optimization process is based on a penalty approach. In the following, the mathematical formulation of such penalties is expressed: ϕ_1 and ϕ_2 are:

$$\phi_1 = 1 + n_k \cdot K_1 \quad \textbf{where} \quad n_k = max\Big(0, \Big\{V_i, V_i^t, V_i^c, V_i^b\Big\}\Big) \tag{10}$$

$$\phi_2 = N_{nodes} \cdot K_2 \tag{11}$$

where K_1 and K_2 represent the amplification factors equal to 10%, while n_k and N_{nodes} are the maximum violation obtained from Eq.s 2-5 and the numbers of connections, respectively.

Functions ϕ_1 and ϕ_2, allow to penalise design solutions which do not satisfy the structural boundaries and/or prefer a higher number of connections. The latter penalty plays a crucial role in simplifying the constructability at the production phase since a limited number of connections leads to a significant decrease of the total number of structural elements to be assembled in the construction site.

The third penalty ϕ_3 relates to Serviceability Limit States (SLS) restrictions on the maximum deflection for steel and timber elements.

$$\phi_3 = 1 + (\delta_{max} - \delta_k) \tag{12}$$

where $\delta_{max} = 15\, cm$ is assumed according to the recommendation provided by Standard codes while δ_k is the maximum displacement experienced by the structure at the middle of the roof.

Furthermore, the environmental OF (OF_2) is introduced. The function has been expressed in the following mathematical form:

$$\begin{aligned} min f(\mathbf{x})_2 = & \overbrace{\sum_{i=1}^{N} \rho_i A_i l_i \cdot GWP^{tot}_{beam/column} \cdot \phi_1 \cdot \phi_3}^{\text{Elements}} \quad + \\ & \overbrace{M_{node} \cdot GWP^{tot}_{node} \cdot \phi_2}^{\text{Connections}} \quad [kgCO_2 - eq.] \end{aligned} \tag{13}$$

where $GWP^{tot}_{beam/column}$ and GWP^{tot}_{node} is evaluated following a Life-Cycle-Assessment methodology. To provide a representative and comparative result for the considered building, the objective function's outcome, deprived of the penalties, is divided by the surface.

Since two materials have been involved in the optimisation process, a proper density value, ρ, is fixed for OF_1 and OF_2. Specifically, $\rho_{steel} = 7850\,kg/m^3$ for steel grade S355, whereas $\rho_{glulam} = 470\,kg/m^3$ for glulam 28h are adopted.

The structural penalties imposed on OF_1 are also considered for OF_2 to guarantee that both functions would have obtained safety configurations.

4 Results

In this section, the results of the optimisation process are collected.

In Figure 2, a zoom on the Pareto-optimal front is reported from the whole spectrum of individuals.

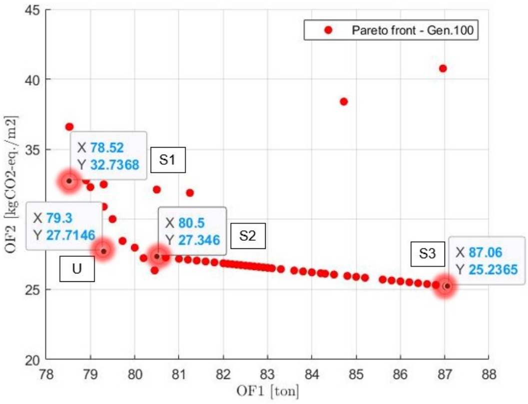

Figure 2: Zoom on the Pareto-optimal front of Scenario 2

The Utopian point method is also used to determine the Pareto-optimal front's best solution. Once more, three further solutions are examined: the front's two extremes and a compelling intermediate solution.
The results in terms of optimised design variables and OF are shown in Table 2.

Table 2: Results of the best solutions for Scenario 2

	U-point solution	**S1**	**S2**	**S3**
OF_1 $[ton]$	79.3	79.3	80.51	87.06
OF_2 $[kgCO_2eq./m^2]$	27.71	32.74	27.35	25.24
H $[m]$	3	3	3	3
div_x	6	6	6	6
div_y	3	3	3	3
Up long.	CHS 355.6x6.3	CHS 355.6x6.3	CHS 355.6x6.3	CHS 355.6x6.3
Up transv.	CHS 406.4x6	CHS 406.4x6	CHS 406.4x6	CHS 406.4x6
Low long.	CHS 114.3x2.5	CHS 114.3x2.5	CHS 114.3x2.5	CHS 88.9x3
Low transv.	CHS 139.7x4	CHS 139.7x4	CHS 139.7x4	CHS 114.3x5
Diagonals	GL 365x570	GL 365x418	GL 365x570	GL 365x570
Columns	GL215x608	GL215x532	GL315x494	GL215x1368

It is possible to detect quite comparable geometric features in any optimal arrangement. The OFs make this evident: the structural and environmental ones deviate from the utopian solution by a maximum of 9% and 15%, respectively. A slight discrepancy once more arises from the assignment of the cross-sections.

It is evident from both the graphic representation and the design variables' optimal values that the fundamental novelty element resides in the mixed-material configurations with glulam diagonals preferred by the optimiser. This solution is chosen for the low-density value of the wood, which is concerned with steel members, leading to lightweight solutions.
Inside the configurations, the steel components are comparatively equal. This may be attributed to the optimiser identifying elements that operate at their maximum capacity and validating the structural specifications.
Conversely, there are slight discrepancies in the designated sections, particularly concerning diagonals and columns. However, diagonals made of wood represent a feasible trade-off solution to counterbalance the potential mass losses compared with the full-steel solutions.
About the cross-section typology, closed steel sections are preferred for each chord cluster, whereas rectangular glulam sections are assigned to diagonals. For steel elements, the use of closed sections rather than open ones is observed by confirming that these work better in terms of structural and environmental performance.

Regarding the geometric arrangement, particularly the number of divisions in both the x and y directions, the optimiser again favours operating with six divisions in the x direction and 3 in the y direction. In terms of roof height, H, all optimal designs have a height of 3 m.

5 Conclusions and Future Developments

This work's primary objective is to define a rational approach for trading off environmental quality objectives with structural complexity already at the early design stages.

The role of environmental emissions is assessed by adopting a multi-objective formulation that undergoes multi-criteria conditions. In the investigated case study, four optimal designs are identified among all the sets of optimal solutions living in the Pareto front. All the selected best configurations suggested that the minimum number of subdivisions leads to an optimal design with an acceptable level of balance among the proposed OFs. Moreover, the importance of the connections on the total OF is confirmed. The number of nodes entirely governs the total GWP and total mass. The introduction of glulam material for diagonals and columns has a significant impact in terms of reducing the structural cost and the environmental impact of optimal designs. The optimiser assigns CHS steel profile to the upper and bottom chords because of their important stress level, while it prefers timber rectangular elements for all the diagonals and columns.

In future developments of the current research, the role of constructability in the preliminary design of such structural topology will be deeply investigated. Additionally, the structural elements which mostly influence the total mass and the total GWP will be assessed by distinguishing the role of the connection respect those of the structural elements. Finally, a comparison between steel-timber mixed and pure steel design solutions will be introduced offering new insights concerning the advantages of considering timber elements in truss structures.

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