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Structural Optimization of a Steel Truss for Sustainability in Parametric Environment – a Case Study

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Although designing a structure is an iterative process by nature, a very limited number of iterations can be done with the traditional methods to reach the near-optimal solution. However, with the development of information technologies, the usage of parametric design in the construction industry has expanded. This paper aims to show the potential benefits of implementing parametric design and optimization techniques in the early structural design process. For this purpose, a simple parametric model of a steel frame with a truss roof system was created and then optimized for minimum mass and a given floor area. The case study demonstrated that the application of parametric design can reduce the Global Warming Potential of the structure by 7.6 % by optimizing the geometry and the cross-sections, leading to a more sustainable solution.

1. Introduction

The construction industry is one of the largest contributors to carbon emissions and energy consumption since globally, it was responsible for 35 % and 38 % in 2019 (Global Alliance for Buildings and Construction, 2020). Due to increasingly stringent regulations, present design approaches attempt to decrease the energy consumption and the carbon emission of the built environment as much as possible. The Life Cycle Assessment (LCA) method enables quantifying buildings' environmental sustainability in a holistic approach. In the case of steel structures, the environmental impact mainly comes from the mass of the structure. Therefore, optimum structural design can decrease the necessary quantity of steel material, which results in reduced CO_2 emissions as well (Cho et al., 2012). However, the calculation of environmental impact usually takes place during the design development phase, when any changes made to the design already have significant time and cost implications. As is widely known, the decisions made in the early design phase have the greatest impact on the building’s performance (Wang et al., 2002), therefore, this is the stage where the generation and examination of alternative solutions can offer the most benefits. Parametric design enables the rapid generation of variations using mathematical and logical rules to define and control geometry. A parametric model provides great flexibility, thereby significantly expediting the design process with an inherently iterative nature. Several studies have shown the benefits of using parametric design methods in the conceptual design phase (Holzer, 2015) and in the design development stage (Hudson, 2010). The scope of its application is constantly growing, also in sustainable design (Zhang et al., 2021) and lifecycle analysis (Kokkos, 2014). However, the available information in the early design stages is usually uncertain and not precise enough, making applying LCA more difficult. Hollberg (2016) defines the lack of the possibility for optimization in the design process as the main research gap in the present techniques of LCA. To solve this problem, the term Parametric Life Cycle Assessment (PLCA) was introduced. According to Säwén et al. (2022), the most promising approach for large-scale buildings is placing both the modeling and calculation in a parametric environment by using the same platform. Furthermore, parametric design methods combined with optimization algorithms have become a powerful tool allowing infinite options to be designed with sophisticated geometries (Zhang et al., 2018). There are multiple studies regarding the application of optimization techniques in structural design. Work done by Tsavdaridis et al. (2015) focuses on the application of structural topology optimization techniques to design steel perforated I-sections. In the study made by Dedea and Ayvaz (2015), a new metaheuristic algorithm called teaching-learning-based optimization (TLBO) is used for the size and shape optimization of structures.

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Weldegiorgis and Dhungana (2020) worked on the optimization of the steel structure for different purposes and had results for the CO_2 emissions during their analysis. The objective of this paper is to investigate the feasibility and reliability of parametric design and optimization processes in the early design stages to reduce CO_2 emissions of the structure. For this purpose, a 3D parametric model of a steel frame with a truss roof system was created and then analyzed and optimized for a minimal mass of the structure with fixed geometry and a total floor area of 300 m^2 with variable geometry.

2. Research method

The framework of this paper relies on the work of Lopes et al. (2021), which has five main steps. In this study, an additional step was integrated (Figure 1) to enable the calculation of the environmental impact of the structure based on the parametric model.Figure 1

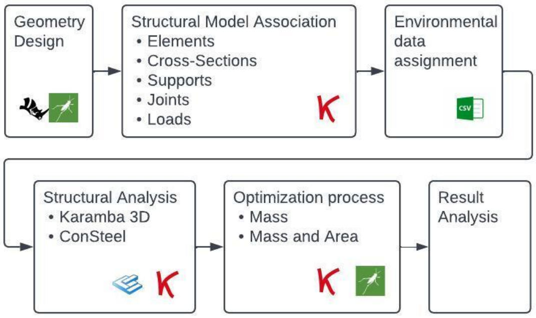

Figure 1: The framework of the research, based on Lopes et al. (2021)

1. Geometry Design: In this stage, the initial architectural concept, building requirements, and the visual programming language algorithm are defined. The algorithm will ultimately determine the geometry. In this paper, the software Rhinoceros3D (2023) and Grasshopper are used for these purposes. The construction form is generated based on the design assumptions that will guide other structural modeling decisions.
2. Structural Model Association: This stage employs components for the automatic generation of the structural model which is linked to the geometry and structural parameters. In this study, Karamba3D (2023) is used to associate finite elements with geometric model components (points, lines, and surfaces).
3. Environmental data assignment: In this stage, the environmental data is assigned to the elements by referencing CSV files in Grasshopper as external databases containing the unit values of the impact indicators. In this study, the database of ÖKOBAUDAT (2023) was used. During the optimization process, the product stage, i.e., the A1-A3 modules of the lifecycle, is considered, and only the Global Warming Potential (GWP) is calculated, where the unit value is 2,270 kg-CO_2eq per 1 ton of steel.
3. **Structural Analysis:** This stage involves calculating loads, reaction forces displacements, and other important information concerning the structural behavior to assess its members' performance. In this study, ConSteel (2023) software was utilized to validate the results obtained from Karamba3D.
4. Optimization process: The objective of this step is to conduct optimization while ensuring the selection of reasonable solutions. In this stage, objective functions (parameters used to assess performance) and constraints are established. The primary optimization goal for this project is to reduce the environmental impact of the structure, focusing on minimizing its mass.
5. Results Analysis: After each optimization run, results are analyzed and checked. This step aims to check the algorithm and observe the limitations of each optimization objective. And, if needed, improving the model and running the optimization algorithm again.

3. Evolutionary solver Galapagos by Grasshopper

In this study, the Galapagos optimization solver was used, which is integrated into Grasshopper. The solver uses evolutionary algorithms to search through a range of possible solutions, seeking to achieve specific design objectives and constraints. It uses a genetic algorithm that operates by evolving a population of potential solutions over successive generations to find an optimal or near-optimal solution to a problem. The behavior of the genetic algorithm is controlled by various parameters, such as the population size (the number of candidate solutions in each generation), the mutation rate (the probability that an individual solution's parameters will be randomly altered), and the termination criteria (conditions that determine when the algorithm should stop). The algorithm typically runs for a specified number of iterations or until a termination condition is met. While optimization algorithms can be powerful tools for finding optimal solutions, they also have certain limitations that should be carefully considered. These limitations can arise from various factors, such as the way the solver works, the quality of input data, and the nature of the problem to be solved. Evolutionary Algorithms do not guarantee a solution. Unless a predefined 'good-enough' value is specified (in a threshold parameter, for instance), the process will tend to run indefinitely, never reaching the answer or, having reached it, not recognizing it for what it is. Galapagos solver works with random values. Therefore, the worst data for a solver is that it has a high degree of noise or chaos. A landscape may be continuous and yet feature so much detail that it becomes impossible to make any intelligible predictions regarding the fitness of a local patch (Rutten, 2010).

4. Case study

4.1 Geometry Design

The geometry design algorithm was made in Grasshopper. Real-time models from Rhino are generated by toggling different input parameters. The model consists of the primary load-bearing elements (i.e., the columns and the trusses) and the stiffening system (i.e., wind bracings and purlins). The model has only one predefined parameter – a starting point at (0,0,0) coordinates. Essentially, three main parameters define the volume of the structure (Figure 2): width of the frame (m), length of the structure (m), and height of the lower truss chord (m). The number of frames (pc), as well as apex height (m), truss height (m), and the number of truss divisions (pc) are also controlled by sliders and connected to the optimization solver component. Truss design controls the web geometry and can be chosen between 4 patterns with or without posts. Additionally, small algorithms are added in this stage to check model geometry and edit it automatically (e.g., adding the frame if the distance between them is more than 6 m).

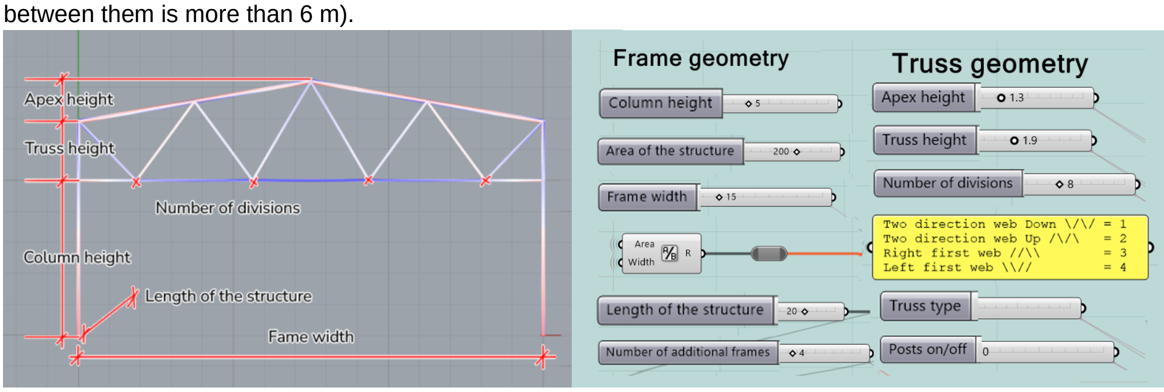

Figure 2: a) Geometry of the structure and its parameters, units in [m], b) Input parameters in Grasshopper, units in [m]

4.2 Structural Model Association and assignment of environmental data

Before the Structural Analysis, the initial geometry design, consisting mainly of points and curves, must be transformed into a structural model with assigned cross-sections, support types, and applied loads. The loads were calculated following Eurocode standards using data derived from the structure's geometry. The following loads were considered besides the deadweight: roof and wall covering, snow load, accidental snow load, and wind load from two directions. Python scripts were made by the authors to perform wind calculations and create load cases. To associate structural elements with the pre-existing geometry, the Karamba3D plug-in was used. It offers built-in components that enable the selection of materials and cross-sections from its library. For this study, only the SHS cross-section library was selected. Numerical load data was converted using specific components and applied to the chosen elements. Since there is no option to generate load combinations in Karamba3D, an algorithm was created to generate them manually. Six load combinations were created: two for the ultimate limit state, three for the serviceability limit state, and one for the accidental limit state, which was utilized in the structural analysis. All the relevant values necessary for the optimization process were extracted from the components and prepared for future utilization. Karamba3D calculates the deadweight of the structure automatically. Therefore, the Global Warming Potential can be calculated by multiplying the mass of the structure and the unit value of the CO_2 emission by using the data from the referenced CSV file. Consequently, the emissions can be dynamically examined when changing the geometry or the cross sections.

4.3 Structural Analysis

To evaluate the results from the Karamba3D one version of the structure was created also in ConSteel FEM software. The Karamba model assembly was modified until the reaction forces and deflections were almost equal in both software. The difference may come in the way programs calculate the deadweight of the structure. The data for both software is collected in Table 1.

Table 1: Comparison of the results from Karamba3D and ConSteel

Reaction forces for the same support	Rx (kN)	Ry (kN)	Rz (kN)	Rxx (kNm)	Ryy (kNm)	Rzz (kNm)	Max. displacement (mm)	Deadweight (kg)
ConSteel	-0.37	0.15	81.29	-0.32	-0.73	-0.01	4.18	14,494
Karamba3D	-0.33	0.12	82.21	-0.27	-0.64	-0.02	4.14	14,151

4.4 Optimization

After the model was validated, first-order analysis was applied during the optimization process, for which the Galapagos evolutionary solver was employed. To achieve a reasonable solution for the optimization goal, a fitness function was introduced. This function comprises several components that need to be minimized. Two types of optimization goals were defined: in the first case, it is aimed to minimize the total mass of the structure when the geometry is fixed and only the cross sections can be changed; in the second case, the goal is to find an optimal geometry along with minimum mass when only the total floor area of the structure is fixed. Additional inputs were defined for the solver as restrictions to check the model for inappropriate behavior and produce a significant output if errors are found. Consequently, the total sum increases dramatically, forcing the solver to explore alternative solutions. The solver is restricted for the following in both cases:
1. Excessive displacement (for instance, if exceeding the span of the frame divided by 300).
2. Highest utilization value is either higher than 95 % or less than 50 %.
3. A condition where the sum of the truss height and apex height is lower than 2 meters (as the algorithm might eliminate the truss by setting both parameters to 0).
4. Angle deviations of the web elements, which should fall within the range of 30 to 60 degrees relative to the bottom chord.
For the optimization process, the termination condition was a time limit of 90 minutes, after which the solver stops.

5. Result and discussion

5.1 Mass Optimization with fixed main geometry

As the CO_2 emission depends on the structure's mass, which is calculated by multiplying it with the factors provided by the manufacturer, the first optimization goal was to minimize the mass of the structure. In this optimization run, the structure's dimensions were manually set and remained fixed at 15x20x5 m for width, length, and height to the bottom chord, respectively. The solver controlled certain aspects of the geometry, as indicated in the second row of Table 2 and illustrated in Figure 2. By modifying these components and seeking the best solution that complies with all set restrictions, the solver found a solution shown in Figure , and its parameters are presented in Table 2.

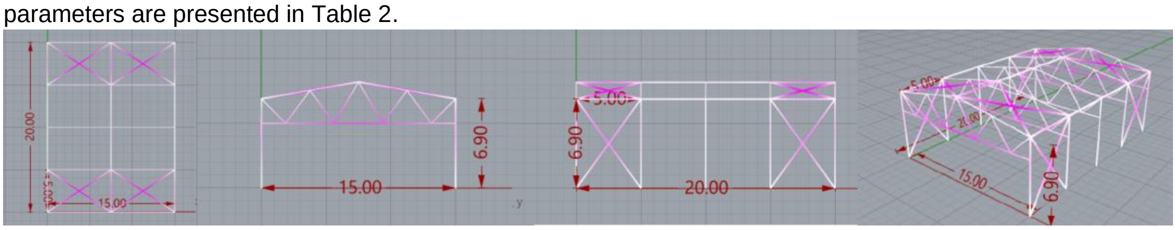

Figure 3: Optimized geometry in Rhino3D, units in [m], Run #1.

Table 2: Mass optimization results with fixed main geometry. Run #1

Unchangeable parameters					Parameters controlled by the solver				
Column height	Frame width	Length of the structure	Number of additional frames	Floor area	Apex height	Truss height	Number of divisions	Truss type	Posts
5 m	15 m	20 m	4	300 m^2	1.3 m	1.9 m	8	1	no
Cross-sections (SHS) according to the EN10210 S235 (mm)									
Columns	Top chord	Posts	Diagonals			Bottom chord		Purlins	Bracing
100x100x5	80x80x5.6	80x80x5.6	80x80x5.6			80x80x3.2		120x120x4	120x120x4
Structural analysis results									
	Mass							Max. Displacement	
	7,093.4 kg							1.09 mm	

To reduce mass, the solver eliminated posts and placed the minimum number of frames necessary for this geometry, ensuring that the distance between frames is less than 6 meters. The added height of the structure is now 3.2 m (1.3 m+1.9 m). The chosen cross-sections are specified in Table 2. The total mass of the structure is approximately 7 tons, with the maximum utilization just below the set upper boundary at 94.9 %. For this structure, the Global Warming Potential is 16,102 kg-CO_2eq.

5.2 Mass optimization with changeable main geometry

In this run, the solver was additionally connected to the width slider, and the length parameter was adjusted to be calculated from the set area of 300 m^2. The height of the columns remained unchanged. The new geometry is depicted in Figure 4, and the results of this run are summarized in Table 3.

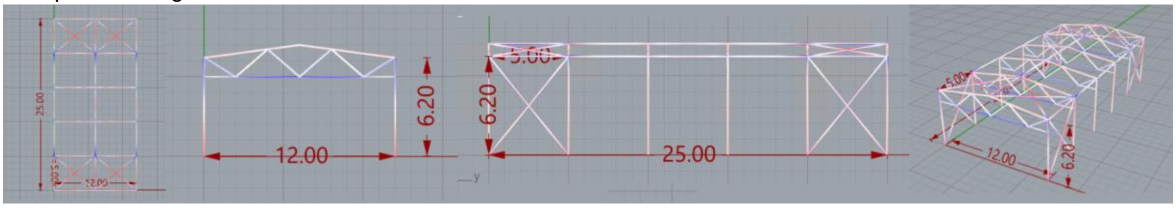

Figure 4: Optimized geometry in Rhino3D, units in [m], Run #2

Table 3: Mass optimization results with changeable main geometry. Run #2

Unchangeable parameters		Parameters controlled by the solver							
Column height	Floor area	Frame width	Length of the structure	Number of additional frames	Apex height	Truss height	Number of divisions	Truss type	Posts
5 m	300 m^2	12 m	25 m	5	0.8 m	1.2 m	6	1	no
Cross-sections (SHS) according to the EN10210 S235 (mm)									
Columns		Top chord	Posts	Diagonals		Bottom chord		Purlins	Bracing
110x110x4		120x120x4	120x120x4	120x120x4		80x80x3.2		110x110x4	110x110x4
Structural analysis results									
		Mass			Max. Utilization			Max. Displacement	
		6555.2 kg			91.30 %			1.00 mm	

The solver modified the structure's geometry to 25x12 m and added 5 frames. The truss geometry also changed, except for the truss type and the presence of posts. The total height of the structure decreased from the previously added 3.2 m in the first run to 2 m in this one. Moreover, the number of divisions decreased from 8 to 6. The cross-sections for columns, top chord, posts, and diagonals increased, while the bottom chord remained the same, and purlins and bracings became smaller. These alterations led to a lower mass of 6.6 tons with a higher utilization rate of 91.3 %. The Global Warming Potential (GWP) in this case is 14,880 kg-CO_2eq.

6. Conclusion

This study presents the possibilities the application of parametric modeling in the initial phase of structural design through an example of a steel frame structure. The main benefit of the applied method is that it combines parametric modeling, structural analysis, and environmental impact calculations on a single platform, suitable for optimization purposes. Two optimization goals were defined: 1) to find the minimum mass for a defined geometry; 2) and to find an optimal geometry along with minimum mass for a defined floor area. Based on the results, allowing the solver to change the geometry of the structure not only accelerates the initial design process but also allows the user to tailor the structure to specific needs. This case study demonstrated that by granting control over the initial geometry to the solver, the mass of the structure was successfully reduced by 538 kg, and therefore the GWP/m^2 ratio decreased by 7.6 %. Since the solver applies random values during the optimization, the obtained results can be local optima, which may vary depending on the initial geometry and the applied time constraint. However, this ability to optimize the structure's geometry proved to be a highly valuable tool for the initial design stage. It facilitated the generation of a design that is not only faster to obtain but also environmentally conscious while meeting the functional and structural requirements as well.

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