OPTIMIZATION OF SUSTAINABLE PROFIT IN THE CONSTRUCTION OF HALL STRUCTURES

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The paper presents the optimization of the sustainable profit in the production of hall buildings. It focuses on single-story halls with either steel or timber frames. The discrete class of optimization is performed with mixed-integer nonlinear programming. The Modified Outer-Approximation/ Equality-Relaxation algorithm is used. Separate optimization models are developed for steel and timber structures, each with two different objectives: sustainable and economic profits, which are subjected to design and dimensioning constraints. The material costs of the structure are defined in detail, while the transportation, machinery and labor costs are calculated as a function of the material costs. The sustainable profit includes eco costs of global warming. A numerical example at the end of the article shows the optimization of sustainable and economic profits in the construction of a hall structure. The calculated sustainable and economic profits in the case of the steel structure are higher than the profits of the timber frame structure due to the high cost of glulam in the market. Nevertheless, the eco costs of global warming in the case of timber construction show a much smaller relative increase compared to the material costs.

Keywords: Timber frame, Steel, Global warming, Material cost, Glulam portal frame.

1 INTRODUCTION

The field of optimizing steel and timber hall structures is a cutting-edge area in structural optimization. Researchers have devised various optimization methods to achieve optimal frame design. O'Brien and Dixon (1997) applied linear programming to the optimal design of portal frames, while Guerlement et al. (2001) minimized the mass of a steel hall using Eurocode 3 (The European Union 2005). Saka (2003) and McKinstray et al. (2015) used a genetic algorithm to find the optimal steel frame design. Kravanja and Žula (2010) optimized the production cost of a steel hall structure using mixed-integer nonlinear programming (MINLP), and Kravanja et al. (2013) presented a parametric MINLP mass optimization of steel industrial halls. McKinstray et al. (2016) achieved the optimal shape of a main steel frame with minimal mass in recent studies. In the field of the timber hall structures, Topping and Robinson (1984) optimized timber frames with sequential linear programming, while Kravanja and Žula (2020, 2021, 2022) applied the MINLP to optimize timber hall frames, obtaining the minimal material costs.

In contrast to the references Kravanja et al. (2013) and Kravanja and Žula (2020, 2021, 2022), this paper is concerned with optimizing the sustainability profit generated in the production of hall structures. A single-story hall structures made of steel and timber are considered, see Figure 1. They are optimized for maximum sustainability profit, taking into account the environmental costs of global warming. The optimization approach of mixed-integer
nonlinear programming (MINLP) is applied. At the same time, an optimal structural hall design, including the optimal number of elements, strength material specifications, and standard dimensions of elements, is also achieved.

2 STEEL AND TIMBER HALL STRUCTURES

The hall under examination serves commercial, industrial and sport needs. It consists of uniform main frames supporting roof purlins, façade rails, and front and rear columns, made of hot-rolled IPE or HEA steel sections. The main portal frames can be HEA steel sections or glulam rectangular sections. The columns of the main frames rest on concrete foundations.

![Figure 1. A single-story steel hall structure.](image)

The analysis of the structure includes the effect of the dead-weight of the structure, the snow load and the horizontal wind load (concentrated on the top of the columns). Forces and deformations are determined using first-order elastic theory. Steel frames are treated as non-sway. Bracing ensures longitudinal stability. The design follows Eurocode 3 (The European Union 2005) for ultimate and serviceability limit states. The structural elements are verified for their resistance to bending moments, axial and shear forces, buckling, lateral-torsional buckling and interactions.

Timber frames are considered as sway. Eurocode 5 (The European Union 2008) is used for the dimensioning. The glulam beams and columns are analyzed for resistance to bending, axial compression, shear, buckling, lateral torsional stability, as well as to stresses at the apex area and interactions.

The vertical deflections of the structural members and the horizontal displacements of the frames are limited by the limits specified in the Eurocodes.

3 OPTIMIZATION

The optimization of hall structures is a complex nonlinear, nonconvex, continuous, and discrete problem. It can be solved by mixed-integer nonlinear programming (MINLP). A general MINLP problem can be formulated as follows, see Eqs. (1)-(4):

$$\min f(x, y)$$

subjected to:

$$g(x, y) \leq 0$$

$$x \in \mathbb{R}$$

$$y \in \{0, 1\}$$
In the general problem formulation, \( f(x,y) \) is the objective function, \( g(x,y) \) represents the (in)equality constraints, \( x \) stands for the continuous variables and \( y \) for the discrete \((0,1)\) variables. In MINLP, at least one of the constraints or the objective function is nonlinear.

Four different optimization models have been created to optimize steel and timber hall structures, two for each material: HALLOPTEP and HALLOPTSP. The first two models (HALLOPTEP) focus on economic profit optimization, while the second two models (HALLOPTSP) focus on sustainable profit optimization. The models have been developed using the upper general MINLP model formulation. The MINLP models include input data, variables, and an objective function that is subjected to various load, stress, resistance, deflection, and dimensioning constraints. Integer logical constraints for topology, standard dimensions, and material strength calculations are also included.

The input data (constants) comprise the span, height, and length of the structure, different material strength alternatives (steel, timber, concrete), different standard/discrete section options, loads (snow, wind), roof and façade weights, material prices, safety factors, etc. Continuous variables in the models represent design factors such as material cost, economic profit, sustainable profit, spacing between structural elements, section dimensions, section properties, etc. Discrete variables are used to calculate the discrete options such as the optimal number of main frames, purlins and rails, standard cross-sections and material strengths. The (in)equality constraints represent the dimensioning/resistance conditions of structural elements, which were briefly mentioned in the previous section.

MINLP is a discrete optimization technique (Kravanja et al. 1998). The optimization models are built in a GAMS environment (Brooke et al. 1988) and solved using the Modified Outer-Approximation/Equality-Relaxation algorithm (Kravanja and Grossmann 1994). The optimization is performed using the MIPSYN package (Kravanja 2010). This approach involves a combination of nonlinear programming (NLP) and mixed-integer linear programming (MILP) subproblems. The continuous NLP optimizations are done using GAMS/CONOPT - generalized reduced-gradient method (Drud 1994) and the discrete MILP calculations are executed using GAMS/Cplex - branch and bound (IBM ILOG CPLEX Optimization Studio 2017).

4 OBJECTIVE FUNCTIONS OF THE ECONOMIC AND SUSTAINABLE PROFIT

Two different objective functions have been defined for the optimization. The first is the objective function of the economic profit obtained in the manufacturing of hall structure, see Eq. (5). The economic profit \( P_E \) is calculated in a simple way by subtracting the material costs \( C_{MAT} \), the transportation costs \( C_{TR} \), the machine service costs \( C_{MASH} \), and the gross labor costs \( C_{LAB} \) from the sales price of the hall structure \( C_S \). The above costs can be treated as decisive costs in construction, see Pšunder et al. (2009). Labor costs are multiplied by an indirect cost factor \( f_0 \) for overheads.

\[
P_E = C_S - C_{MAT} - C_{TR} - C_{MASH} - C_{LAB} \cdot f_0
\]  

(5)

The material costs are determined by Eq. (6), where \( C_{Mi} \) represents the material unit prices, \( \rho_i \) strands for the volume masses and \( Vol_i \) denotes the volumes of the hall structural elements for three different materials (\( i \): steel, timber and concrete). The material costs of the hall structures are detailed in Kravanja and Zula (2022).

\[
C_{MAT} = C_{Mi} \cdot \rho_i \cdot Vol_i \quad i \in I
\]  

(6)

In this article, the other costs are calculated as a function of the calculated material costs, taking into account the share of each cost in the total cost of the construction. Referring to the
EUROSTAT instructions and the methodology of the Chambers of Commerce in Central Europe (Pšunder et al. 2009), the share of material costs $DC_{MAT}$ makes about 60%, the share of transportation costs $DC_{TR}$ makes 5%, the share of machine service costs makes $DC_{MASH}$ 10%, and the share of labor costs $DC_{LAB}$ makes 25% of the total construction costs (100%). The objective function of economic profit is thus defined by Eq. (7) as follows:

$$P_E = C_S - C_{MAT} \cdot (1 + \frac{DC_{TR}}{DC_{MAT}} + \frac{DC_{MASH}}{DC_{MAT}} + \frac{DC_{LAB}}{DC_{MAT}} \cdot f_0) \quad (7)$$

The second objective function defines the sustainable profit $P_S$ obtained in the production of hall structure, see Eq. (8). $C_{GW}$ is the global warming price and $F_{CEEFI}$ is a carbon footprint emission factor for three different materials ($i$: steel, timber and concrete).

$$P_S = P_E - C_{GW} \cdot F_{CEEFI} \cdot \rho_i \cdot Vol_i \quad i \in I \quad (8)$$

5 NUMERICAL EXAMPLE

A numerical example of optimizing a hall structure with dimensions of 17 m in span, 75 m in length, and 6 m in height is presented. Two structure types of the hall are considered: with steel and timber main frames. The hall is subjected to various loads, including its own weight, roofing weight of 0.20 kN/m$^2$, façade cladding weight of 0.15 kN/m$^2$, snow of 0.90 kN/m$^2$, and horizontal wind of 0.50 kN/m$^2$. The cost of steel is 1.45 €/kg, the cost of glulam is 700 €/m$^3$ and that of concrete is 110 €/m$^3$. Factor $f_0$ is 2.50, $C_{GW}$ is 0.116 €/kg CO$_2$ eq. and $F_{CEEFI}$ is 2.35 kg CO$_2$ eq./kg for steel, 0.90 kg CO$_2$ eq./kg for glulam and 308.20 kg CO$_2$ eq./m$^3$ for concrete. The selling price of the hall structure $C_S$ is 300,000 €.

5.1 Hall Structure with Steel Portal Frames

The optimization models HALLOPTEP and HALLOPTSP for steel were used. A steel hall structure was defined with different topology alternatives of structural elements, different IPE and HEA standard profiles and different steel grades, which together give $1.4226 \cdot 10^{13}$ different structural alternatives - one of which is optimal.

![Figure 2. Optimal steel hall structure.](image)

The MIPSYN computer program took about half an hour of work to find two optimal results. The optimal economic profit of € 49,580 was found in the 41$^{st}$ MINLP iteration, and the best sustainable profit of € 28,399 was calculated in the same iteration. In both cases, the same designs were obtained with the same number of structural elements, cross-sections and material qualities, see Figure 2. The optimal topology of 16 portal frames, 10 purlins and 8 façade rails,
was obtained. Steel S 355 was calculated. Note that the material costs of the structure were € 109,274. The environmental costs of global warming reached € 21,181, an additional 19 % increase to the material costs.

5.2 Hall Structure with Glulam Portal Frames

The optimization models HALLOPEP and HALLOPTSP for timber were employed. The hall structure was designed with various topologies of elements, steel and glulam cross-sections, and steel grades, resulting in $6.4240 \cdot 10^{13}$ possible combinations. The material chosen for glulam was GL28h. The optimal economic profit was achieved in the 54th iteration and amounted to € 15,653. The optimal sustainable profit was reached in the 751st iteration and amounted to € 978. For both optimizations MIPSYN needed about one working hour. Both optimizations resulted in the same structural design, consisting of 16 portal frames, 10 purlins and 8 façade rails. The cross-sections of members can be seen in Figure 3. Steel S 355 was obtained. The material costs of the structure were € 124,078, while the eco costs of global warming yielded € 14,675, an additional 12 % increase to the costs of materials.

![Figure 3. Optimal hall structure with glulam portal frames.](image)

6 CONCLUSIONS

The study focuses on optimization of the sustainable profit in the production of hall structures. Two types of hall structures are considered, structure made of steel, and another made of timber portal frames. The optimization is accomplished through a mixed-integer nonlinear programming using the Modified Outer-Approximation/ Equality-Relaxation algorithm. Optimization models for hall structures have been developed, separately for steel and separately for timber frame types. In the models, the objective functions of economic and sustainable profits are subjected to design and dimensioning constraints. The material costs of the steel and timber structures are defined in detail, while the other costs are calculated as a function of the material costs, since the proportions of the different types of costs in the total construction costs are known.

The paper concludes with a numerical example showing the optimization of economic and sustainable profits in the fabrication of a hall structure. This is a very specific example. Here, in the case of steel hall construction, about 3 times better economic profit and about 30 times better sustainable profit were calculated compared to timber frame design due to the high unit price of glulam in the market. Nevertheless, the eco costs of global warming in the case of timber construction showed a much smaller relative increase compared to the material costs. In both cases, the same topologies are obtained, but with different cross-sections.
The presented optimization of the economic and sustainable profit proved to be very useful for a quick comparison of hall designs with different material options, especially in the conceptual design phase.

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