SUSTAINABILITY PROFIT GAINED BY THE OPTIMIZED CLAMPED BEAMS

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Abstract The paper presents the optimization of the sustainability profit achieved by the production of clamped beams in civil engineering. It proposes to design a range of beams using three different material alternatives: structural steel, reinforced concrete and glulam. For this reason, three optimization models of beams are developed for the three materials. In addition, two different objectives are defined for each material alternative: for the economic profit and for the sustainability profit (which includes the eco costs of global warming). The proposed objectives are subject to the design, resistance and deflection constraints of the clamped beam, which are determined in accordance with the specifications of Eurocodes 2, 3 and 5. The mixed-integer non-linear programming (MINLP) approach is used to find most advantageous material alternative of the beams. GAMS /Dicopt is used. The numerical example presented at the end of the paper clearly shows that reinforced concrete beams have the highest economic and sustainability profit.

Keywords:
sustainability profit,
GHG emissions,
optimization,
mixed-integer non-linear programming,
MINLP

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1 Introduction

The paper deals with the optimization of the sustainability profit achieved by the production of clamped beams in the area of civil engineering. In this case, the sustainability profit is a sum of the economic profit and eco costs of global warming. It is assumed that a number of beams are designed using 3 different material alternatives: glulam, structural steel and reinforced concrete. The objective of this paper is to find the optimal design of the clamped beam subjected to the highest sustainability and economic profit, performed by mixed- integer non-linear programing approach.

In the areas of sustainability and optimization, various optimization methods and different goals have been proposed. For example, Zaforteza et al. (2009) reported the optimization of CO_2 emissions and production costs of concrete constructions using simulated annealing (SA). Camp and Huq (2013) proposed the calculation of optimal concrete frames with a hybrid big bang-big crunch algorithm (BB-BC), where the objective was to minimize the total cost or CO_2 emissions. Alonso and Berdasco (2015) presented the carbon footprint calculations of some wood products. Li et al. (2017) introduced a topology optimization of welded box girders with minimal greenhouse gas emissions, where an improved ground structure method (IGSM) was applied.

2 MINLP model formulation

Since the problem of clamped beam is the non-linear discrete-continuous optimization problem, the MINLP is used for the solution and can be formulated as follows:

$$\begin{gathered}
\min \ sep = f(\mathbf{x},\mathbf{y}) \\
\text{subjected to:} \ \ m_s(\mathbf{x},\mathbf{y}) \le 0 \quad s \in S \\
\mathbf{x} \in X = \{\mathbf{x} \in R^n \colon \ \mathbf{x}^{\mathrm{LO}} \le \mathbf{x} \le \mathbf{x}^{\mathrm{UP}}\} \\
\mathbf{y} \in Y = \{0,1\}^m
\end{gathered}$$

where **x** are the continuous variables and **y** are the discrete (0, 1) variables. Function *sep* is the objective function for the economic profit and for the sustainability profit (which includes eco costs of global warming). m_s (**x**,**y**) represents the design, resistance and deformation constraints.

3 Numerical example

The example shows the optimization of 800 equal clamped beams. Each beam is 8.0 meters long, subjected to the combined effect of the dead-weight, the permanent load of 9.0 kN/m (g) and the imposed variable load of 12.0 kN/m (q), see Fig. 1.

It is proposed to make each clamped beam from three different material alternatives: glulam, structural steel and reinforced concrete. At this point, the comparison and competitiveness between these 3 beam materials has been investigated for different material and dimensional variants and for 2 different objectives, i.e. for the optimization of sustainability and economic profit.

For extensive and time-consuming optimization problems, we usually use the program MipSyn (Kravanja, 2010). Since the optimization problem of the clamped beam is a single discrete non-linear problem, Dicopt (Grossmann, 2002) was chosen for the application. 6 different optimization models for the clamped beam (CLAMBOPT) were modeled as a combination between 3 various materials (wood, steel and concrete) and 2 various objective functions. GAMS (General Algebraic Modelling System), (Brooke et al., 1988), was employed for modeling and input/output interpretations. Each model consists of the input data (scalars), variables, and the objective function, which is subjected to the design, loading and dimensionig (in)equality constraints. These constraints were defined in accordance with the Eurocode standards: Eurocode 2 (2004) for concrete, Eurocode 3 (2005) for steel and Eurocode 5 (2004) for wood. The clamped beams were tested for bending moment, shear force and lateral torsional buckling. Vertical deflections were also checked.

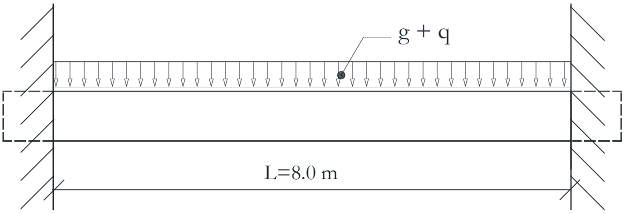

Figure 1: Clamped beam.

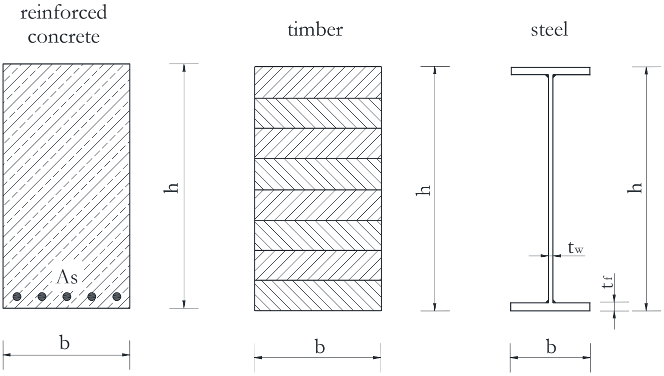

Figure 2: Cross sections of the clamped beam.

The clamped girder super-structure contains of 3 different materials. The glulam girder super-structure comprises 131 rounded dimensional variations for the section height and 101 different rounded dimensional variation for the section width. The steel girder super-structure comprises eight different dimensional variations of standard steel plate thicknesses for flanges and webs separately, 1051 rounded dimensional variations for flange width and 1301 rounded dimensional variations for web height and three different steel grades. In addition, thirteen standard steel reinforcing bars, seven different concrete grades 101 rounded dimension variants for the section width (rounding up to whole centimeters) and 131 rounded dimension variants for the section height are involved in the concrete girder super-structure.

The specified material and dimension variants (binary variables) result in 13 231 design variants for the wooden beam, 262 531 392 different design variants for the steel beam and 1 204 021 different design variants for the concrete beam.

2 different objective functions were proposed for 2 different defined criteria. The 1st criterion of optimization comprises the maximization of the economic profit (P_{EP} [€]) of 800 identical beam structures. The economic profit is calculated as the sum of the self-manufacturing material, labor cost, selling price and overhead cost. The objective function was defined separately for 3 different materials, see Eq. (1). N is a number of clamped beams ($N = 800$), C_{SP} [€] is the sales price of a clamped beam, $C_{\mathrm{MP}j}$ [€/kg] stands for the material unit prices of ($j \in J$: glulam, protection and impregnation paint for the wood beam; structural steel, gas consumption, electrodes and anticorrosion-resistant paint for the steel beam; and formwork slab-panels, concrete and steel reinforcing bars for the concrete beam). ϱ_j [kg/m^3] is the corresponding unit mass and V_j [m^3] is the volume. While $C_{\mathrm{LC}i}$ stands for the labor cost per hour [€/h], t_i [h] is the time required for ($i \in I$: painting and impregnating of the glulam; welding, cutting and painting the steel beam; and curing, vibrating and placing the concrete, placing and cutting the reinforcement, and paneling the concrete beam), and f_{O} is an indirect overhead cost factor ($f_{\mathrm{O}} = 2$). For more details on the cost factors used in the economic objective function, see (Jelušič, 2017) and (Kravanja, 2017).

$$\max P_{\mathrm{EP}} = N \cdot \left(C_{\mathrm{SP}} - C_{\mathrm{MP}j} \cdot \varrho_j \cdot V_j - C_{\mathrm{LC}i} \cdot t_i \cdot f_{\mathrm{O}} \right) \tag{1}$$

The 2nd criterion is to maximize the sustainability profit (P_{SP} [€]), which is calculated for 800 beams as the sum of the economic profit and the eco costs of global warming caused by the beam production (EVR, 2018). The objective function was defined separately for 3 materials, see Eq. (2). C_{W} (€/kg CO_2 eq.) is a price of global warming, 0.116 €/kg CO_2 eq. (EVR, 2018), ϱ_m [kg/m^3] and V_m [m^3] are the corresponding units of mass and volume respectively, and $f_{\mathrm{CO2}m}$ is the emission factor of the carbon footprint ($m \in M$; for the glulam beam, steel and reinforced concrete beam, respectively). The carbon footprint emission factor used in the study is 0.11–0.16 kg CO_2 equivalent/kg for concrete, 2.43 kg CO_2 equivalent/kg for steel reinforcing bars, 0.69 kg CO_2 equivalent/kg for glulam and 1.72 kg CO_2 equivalent/kg for steel.

$$\max P_{\mathrm{SP}} = P_{\mathrm{EP}} + N \cdot \left(-C_{\mathrm{W}} \cdot f_{\mathrm{CO2}m} \cdot \varrho_m \cdot V_m \right) \tag{2}$$

Table 1: Results of the clamped beam optimizations.

Criterion		Reinforced Concrete C 50/60	Laminated timber GL24h	Steel S 235
1.*	**Economic profit (€)**	**624,968**	**292,227**	**94,211**
	b (cm)	32.0	41.0	27.9
	h (cm)	45.0	41.0	41.9
2.*	**Sustainability profit (€)**	**540,531**	**252,734**	**27,761**
	b (cm)	32.0	41.0	27.9
	h (cm)	45.0	41.0	43.9

* 1. Economic profit; 2. Sustainability profit

Table 1 shows the optimization results for 2 different objective functions and 3 different materials. The results show that concrete beams have the highest economic and sustainability profit, while steel beams have the worst performance for all criteria.

4 Conclusion

The paper presents the optimization of the sustainability profit achived by the production of clamped beams in the area of civil engineering. The optimal solutions are calculated based on 2 different objective functions, i.e. economic profit and sustainability profit. The optimizations of the beam alternatives are performed by the MINLP approach. The numerical example clearly shows that reinforced concrete girders have the highest economic and sustainability profit, while steel girders have the worst performance on all criteria.

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