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OPTIMIZATION OF STEEL FRAME STRUCTURES BASED ON DIFFERENTIAL EVOLUTION ALGORITHM

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Abstract. *Steel structural design is an integral part of the building construction process. So far, various methods of design have been applied in practice to satisfy the design requirements. This paper attempts to acquire the Differential Evolution Algorithms in automatization of specific synthesis and rationalization of design process. The capacity of the Differential Evolution Algorithms to deal with continuous and/or discrete optimization of steel structures is also demonstrated. The goal of this study is to propose an optimal design of steel frame structures using built-up I-sections and/or a combination of standard hot-rolled profiles. All optimized steel frame structures in this paper generated optimization solutions better than the original solution designed by the manufacturer. Taking the criteria regarding the quality and efficiency of the practical design into consideration, the produced optimal design with the Differential Evolution Algorithms can completely replace conventional design because of its excellent performance.*

1 INTRODUCTION

The use of steel frame structures for large, single and multi-storey buildings such as warehouses, distribution/logistics centers, retail outlets, sports halls or the building frame of factories for commercial/industrial purpose permits the creation of buildings with large, uninterrupted floor areas. The most common form of single-storey building follows the form of a large shed and is referred to as middle and long-span building. According to recent survey in Germany [1], roughly 87% of steel frame structures of mentioned above buildings refer to two-hinged frames. With its popular and broad application in developing countries like Vietnam, the need to use the similar type of frame structures is especially great.

In order to achieve the optimal structure weight as well as lower production cost, the application of built-up I-sections and/or a combination of built-up I-sections with hot-rolled profiles in the design of steel frame structures was broadly applied in the design process. So far, various methods and strategies have been applied in practice to satisfy the design requirements. In the face of increase in price of materials, the civil engineers and the manufacturers are forced to reduce the costs of construction and shorten the implementation period to maintain their competitiveness. As a result, a new design trend was born: the use of the analysis and design software to evaluate feasible design options, replacing the conventional design methods.

Due to the diversification of structural optimization problems, most structural optimization problems can be classified as size, shape and topology optimization [2]. The main application of optimal design of steel structures is the size optimization, because this method is possible to minimize the weight of structures.

This paper attempts to apply the Differential Evolution Algorithm (DE-Algorithm) as optimization algorithm in automatization of specific synthesis and rationalization of design process. The goal of this study is to propose an optimal design of steel frame structures using built-up I-sections and/or a combination of standard hot-rolled profiles. In addition, the frame structures are analyzed with the warping torsion option which includes the formulation of beam elements with seven degree of freedom per node.

2 METHODOLOGY

According to the goal above described, this paper presents optimal design problems concerning frame structures, the DE-Algorithm and optimization synthesis system. The system developed consists of the integrated structural analysis program, the data module, the optimization modules and the stresses module.

2.1 Optimal design problems

The characteristics of frame structures such as geometry, materials, cross-sections of frame members, loads show that many parameters are taken into consideration in the optimum design of a frame structure. Furthermore, optimum design problems are related to stability, safety, serviceability of structures and mathematical optimization methods.

For the optimal design of frame structures, the dimensions of cross-sections of each frame member must be selected from the hot-rolled profile sections or built from the steel plates, which are chosen in the "list of raw materials". With the identified variables of the structure, the objective function is defined based on minimizing the weight/cost of the structure. The constraints should satisfy the verification of carrying capacity including stability conditions and the verification of serviceability regarding displacements. For the stability conditions, the frame structures are analyzed by a structural analysis program with the warping torsion which includes the formulation of beam elements with seven degrees of freedom (7-DOF) per node. The bracing systems, purlins, the roof and wall structures in the building are taken into consideration by applying the supports and springs in the perpendicular plane to the frame. The constants of structural design are geometry, material, load combinations and location of building.

The cost function is the minimum weight of structure (Equation 1) or the minimum cost of building while simultaneously satisfying all strength and stiffness performance requirements under loading conditions. It is expressed as follows:

$$W = \sum_{i=1}^{nm} A_i \rho_i L_i \tag{1}$$

Where the subscript i denotes the group number, nm is the number of members, W is the weight of the structure, A_i is the cross-sectional area of members, ρ_i and L_i are the density and the length of member.

At the end of each iteration the structure must be analyzed to evaluate the constraints such as stresses, local buckling, displacements and explicit bounds on the design variables.

The stress constraints should satisfy

$$\sigma_{il} \leq \sigma_{il}^{P},\ i = 1,\ 2,\ \ldots,\ nm \tag{2}$$

Where σ_{il} is the maximal stress of member i, $\sigma^{P}{}_{il}$ is the permissible stress of the member i in the load case l.

The displacement constraints should satisfy

$$\left|\Delta_{jl}\right| \leq \left|\Delta^{P}{}_{jl}\right|,\ l = 1,\ 2,\ 3,\ \ldots,\ nlc;\ j = 1,\ 2,\ \ldots,\ p \tag{3}$$

Where Δ_{jl} is the displacement of structure, $\Delta^{P}{}_{jl}$ is the permissible displacement under the load case l, p is the number of constrained displacements and nlc is the number of load cases.

The upper and lower bound of design variable constraints are imposed as

$$\begin{aligned} &D_k^L \leq D_k \leq D_k^U,\ k = 1,\ 2,\ \ldots, ng \\ &D_k \in S = (S_d \left| d = 1,\ 2,\ \ldots,\ ns \right.) \end{aligned} \tag{4}$$

Where D_k^L and D_k^U are the lower and upper bounds of S, S and ns are the set and the number of available sections or the steel plates in the "list of raw materials" respectively.

2.2 The DE-Algorithm

In 1997, the Differential Evolution Algorithm was introduced by K. Price and R. Storn [3]. The main idea of the DE-Algorithm is to use vector differences in creation of new trial candidates to find better solutions. For each population, the DE-Algorithm iterates through the population and creates the trial candidates by vector mutation and a variant of uniform crossover. The selection between parent vector X_j and each trial candidate U (see Figure 1) is straightforward and simple [5]: (a) if both compared solutions are feasible, the one with better objective function value is selected, (b) if both compared solutions, one is feasible and another is infeasible, the feasible one is selected, (c) if both compared solutions are infeasible; the solution with less violation is better.

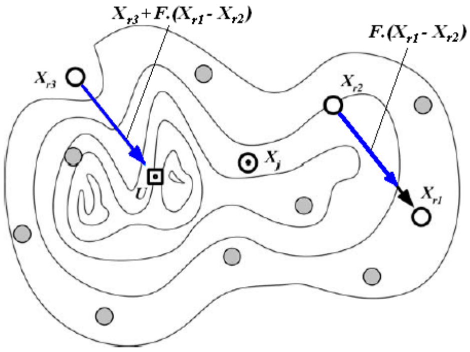

Figure 1: The differential vector and a trail candidate *U* [4]

In following steps, the optimization process based on DE-Algorithm is presented.

S1: Create initial population *P*, each individual of *P* is defined by stochastic method or

$$D_{k,i} = D_k^L + rnd(0,1) \times (D_k^U - D_k^L) \quad (5)$$

S2: Analyse and evaluate the frame structure with initial population *P*. Save the analysis results such as displacements, stresses and cost function value C_P.

S3: Create trial candidates by selecting $P[X_{r1}]$, $P[X_{r2}]$ and $P[X_{r3}]$ where $i \neq r1 \neq r2 \neq r3$.

$$U[i] = P[X_{r3}] + F \times (P[X_{r1}] - P[X_{r2}]) \quad (6)$$

S4: Analyse and evaluate the frame structure with trial candidates $U[i]$. Save the analysis results such as displacements, stresses and cost function value C_T.

S5: Compare the cost function value of vector C_P with the value of trial candidates C_T.

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If CT better than CP then
      P'[i]=U[i]
Else
      P'[i]=P[i]
End if
P[i]=P'[i] (Replace initial population P with P')
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S6: Repeat the optimization process from step 3 to step 5 until the termination criteria are reached. Find the best individual of the last population with the best cost function value.

2.3 Synthesis system

The optimization-based design process with DE-Algorithm of steel frame structures which is showed in Figure 2, consists of a number of steps. The first two steps are to formulate the design task, i.e. the design variables, the design constants, the design boundaries, the design objectives and the necessary cross-sectional data are defined. In the next step, the synthesis process is connected to an optimization program in order to determine the design variables. With a structural analysis program, the displacements, internal forces and stresses are calculated and then the design boundaries and design objectives are identified by the optimization process.

The DE-Algorithm, itself cannot solve the optimization problems. Therefore, the development of a program system is needed in order to optimize the steel frame structures. To achieve this purpose based on the DE-Algorithm application, a computer-based program with the following main modules: “Data process”, “Stress module” and “Optimization modules” has been coded. The necessary data of the structure related to the next steps of optimization process are carried out by the module “Data process". This module performs the data exchange between the optimization program and the structural analysis program such as import and export function. The stresses of structural members are checked by the “Stress module” in accordance with the various design norms. In this paper, the norm EC-3 is applied. The “Optimization modules” includes the minimization of the weight of structure and/or the cost of building. Another option of this module is to determinate the optimal frame spacing of building.

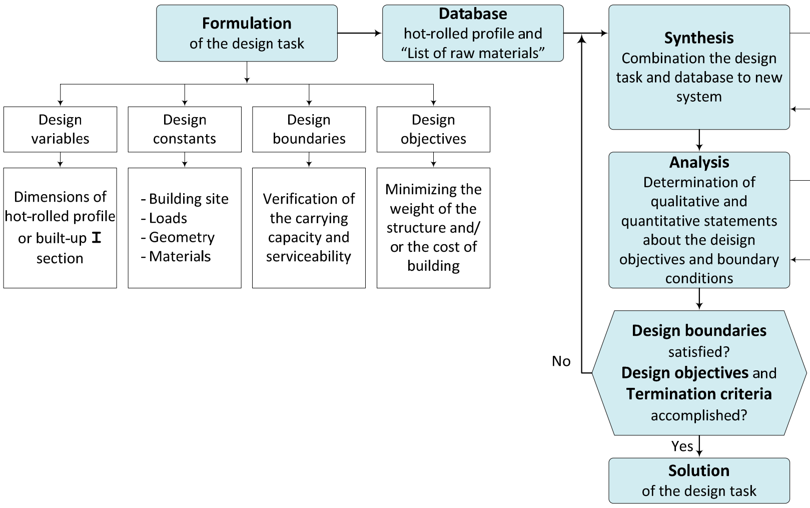

Figure 2: Optimization-based design process of steel frame structures

3 TEST CASES AND RESULTS

The efficient and robust DE-Algorithm is applied to optimize the typical steel frame structures, which are as follows:

Structure 1: bowstring frame support glass facade

Structure 2: frame with L=27.10*m*

Structure 3: frame with truss system L=29.40*m*

3.1 Structure 1

The bowstring frame support glass facade was referred to [6]. The bowstring frame which consists of seven dependent frames and the detailed model of the dependent bowstring frame are shown in Figure 3.

Due to the fact that the circular hollow section offers better resistance to lateral torsional buckling than the I-sections, the circular hollow sections are used for this optimization problem. The optimization variables are divided into following groups: group 1 for cross-section of main columns and group 2 for cross-section of all struts, group 3 for pre-tension force inside and outside of cables.

In the optimization design, the objective function is the minimum weight. The design constraints which are horizontal and vertical displacements of nodes, stresses of structure members, lateral-torsional buckling as well as local buckling are taken into account. After 30 generations, the optimization results of structure 1 are shown in Figure 4 and Table 1.

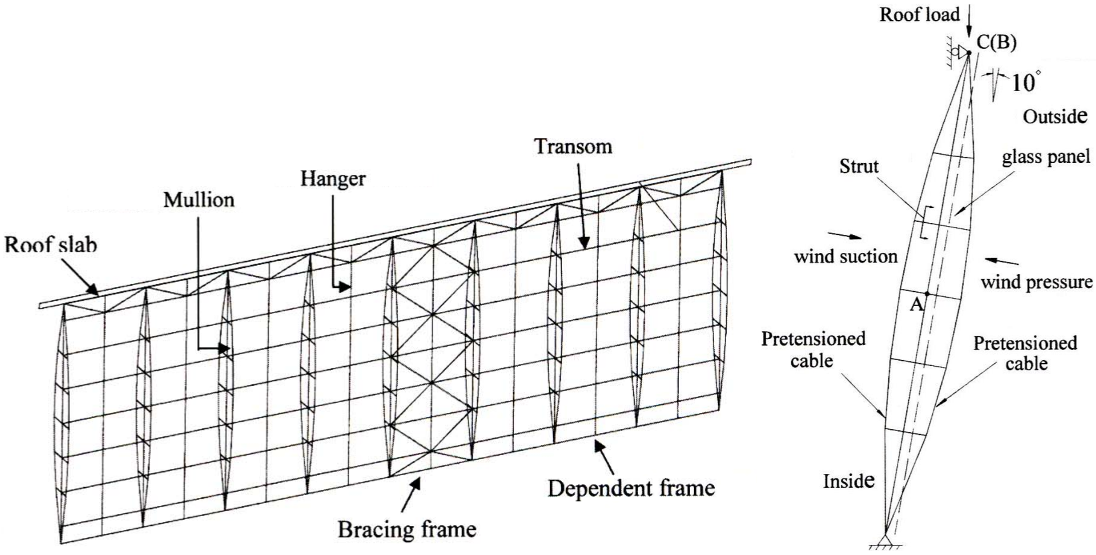

Figure 3: The steel frame of structure 1 [6]

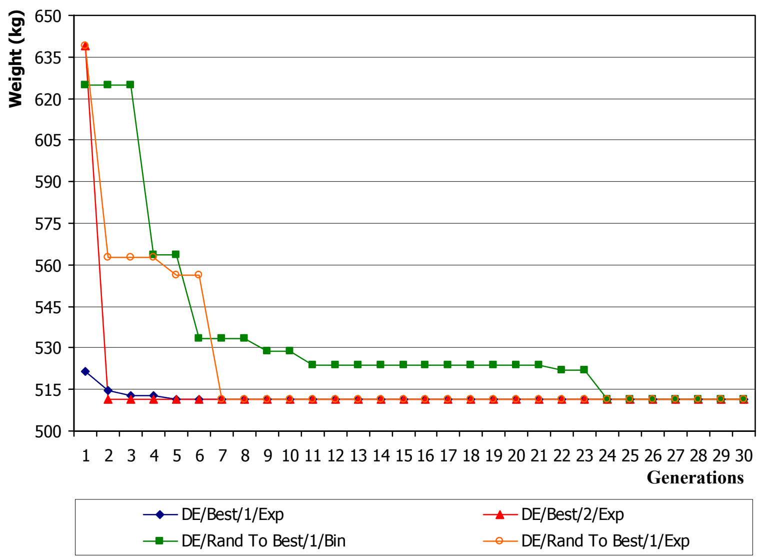

Figure 4: Optimization results of structure 1

Strategy	Weight (*kg*)	Structure 1 (*kg*)	Percentage (*%*)
DE/Rand to Best/2/Exp	511.5		72.4
DE/Best/2/Exp	511.5	706.9	72.4
DE/Best/1/Exp	511.5		72.4
DE/Rand To Best/1/Bin	511.5		72.4

Table 1: Optimization results of structure 1

These results indicate that the optimum weight obtained, using the DE-Algorithm, is 27.6% better than the existing results. With the application of the DE-Strategies, the result of optimal design is 511.5*kg* (Table 1), which means that the saving material is 195.4*kg* per frame and approximately 1.76*tons* for the whole structure.

3.2 Structure 2

The frame structure with geometry and cross-sections (see Figure 5) was designed and manufactured by a well-known German company [7].

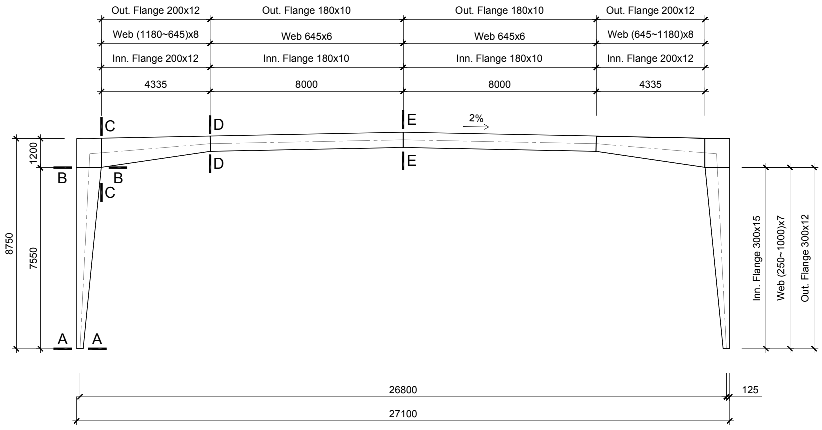

Figure 5: The steel frame of structure 2

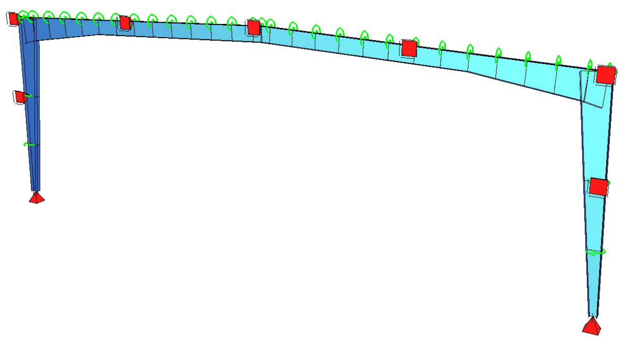

Figure 6: The computer model of structure 2

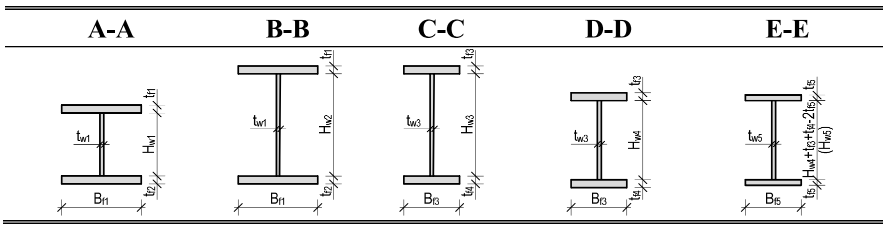

Table 2: Cross-sectional dimensions of structure 2

The optimization variables included sections of the frame from A-A to E-E (see Figure 5 and Table 2). The number of optimization variables of tapered column and rafter is 12, the number of variables of straight rafter is 2, the number of variable for frame spacing B is 1, and thus the total variables for optimization of the structure 2 are 15 variables.

The objective function of this optimization problem is the minimum cost of the building. In addition to minimum cost, another aspect of this optimization is finding the optimal frame spacing of the building. The objective function is considered not only as the minimum weight of the frame structure, the cost of the finishing frames but also the price of trapezoidal profiles of the roof and reinforced-concrete foundations. The design constraints which are horizontal and vertical displacements of nodes, stresses of structural members, lateral-torsional buckling as well as local buckling are taken into account.

The structure is analyzed by the SOFISTiK program with the warping torsion option which includes the formulation of beam elements with seven degrees of freedom (7-DOF) per node. The lateral supports of the frame structure, which support perpendicularly to the plane of the frame, are shown in Figure 6.

After 30 generations, the optimization results of structure 2 are shown in Figure 7, Figure 8 and Table 3.

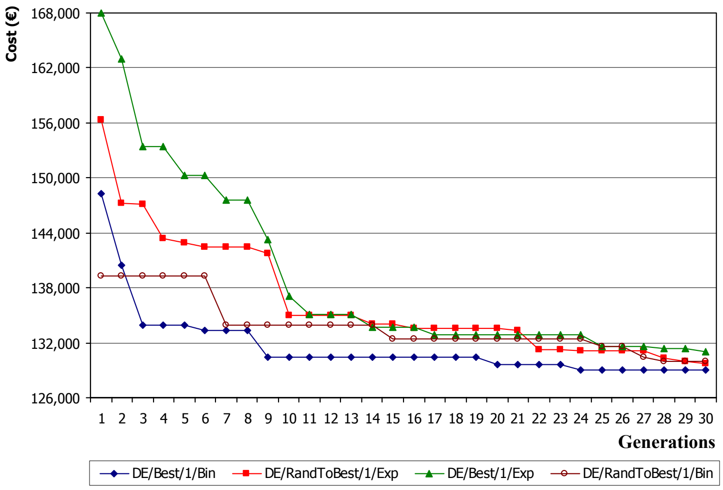

Figure 7: Optimization results of structure 2

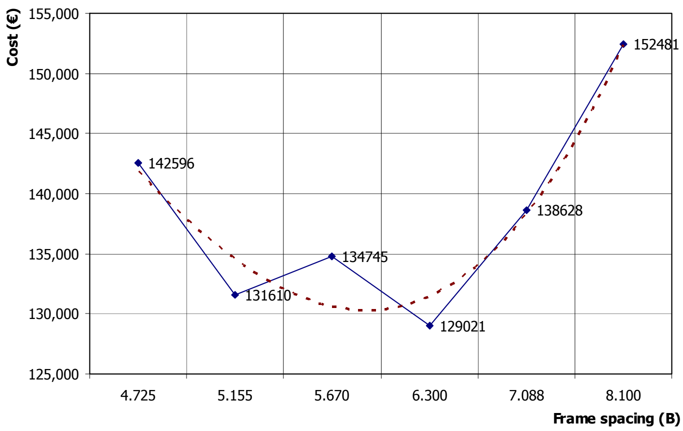

Figure 8: The relation between frame spacing *B* and the cost of building

Strategy	Cost (€)	Structure 2 (€)	Percentage (%)
DE/Best/1/Bin	**129020,70**		**90.9**
DE/Best/1/Exp	130986,00	141833,80	92.4
DE/Rand to best/1/Bin	129984,60		91.7
DE/Rand to best/1/Exp	129714,40		91.5

Table 3: Optimization results of structure 2

Based on the optimization results, the optimal value of 15th variable *B*, whose value are mostly present in the optimization process, is 6.30*m* and the minimum cost also correspond to this value. The trendline in Figure 8 (the dotted line) shows that the obtained optimal frame spacing is appropriate to the recent survey [1] and also to practical design from 5.0*m* to 7.0*m*.

These results indicate that the frame spacing and the cost of the building obtained, using the DE-Algorithm, is approximately 10% better than the result designed by manufacturer. With the use of *DE/Best/1/Bin* strategy (Figure 7), the best result of optimal design is 129.020,70 €, which means that the saving cost is ca. 13.000,00 €.

3.3 Structure 3

The frame structure with geometry and cross-sections (see Figure 9) was designed and manufactured by a well-known German company [8].

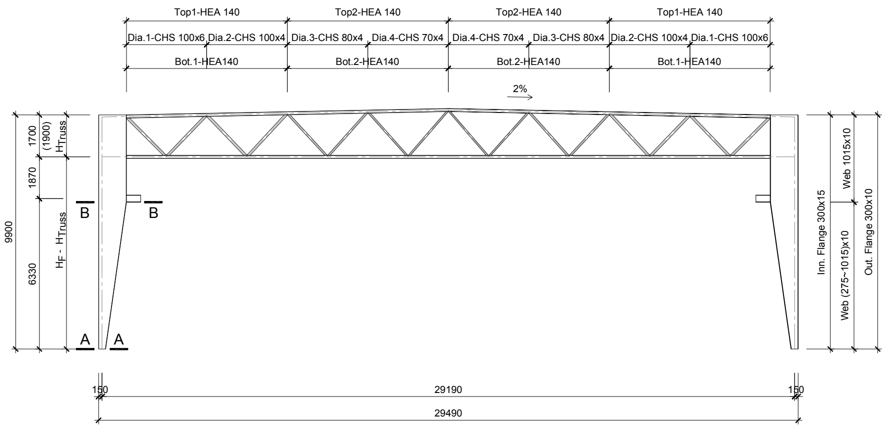

Figure 9: The steel frame of structure 3

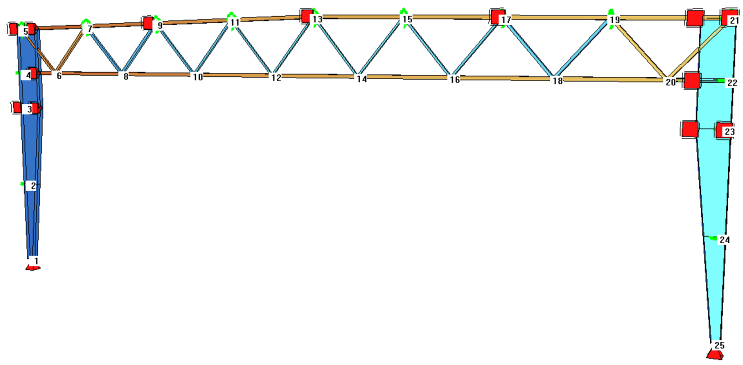
Figure 10: The computer model of structure 3

As mentioned in structure 2, the optimization variables of the frame structure 3 included 2 sections of the frame A-A, B-B and 8 cross-sections of the truss system, which are 2 sections at top, 2 sections at bottom and 4 sections at diagonal members of the truss (see Figure 9). The number of optimization variables of the columns is 6, the number of variables of the truss system is 8, and thus the total variable is 14.

In the optimization design, the objective function is the minimum weight. The design constraints which are horizontal and vertical displacements of nodes, stresses of structure members, lateral-torsional buckling as well as local buckling are taken into account.

The lateral supports of the frame, which support perpendicularly to the plane of the frame, are shown in Figure 10. The structure is analyzed by the SOFISTiK program with the warping torsion option which includes the formulation of beam elements with seven degrees of freedom (7-DOF) per node.

The optimization results of structure 3 are shown in Figure 11, Figure 12 and Table 4. In the first case, with the height of the truss at the support is 1.7*m*, the weight of the frame is ca. 10% less than the weight by manufacturer (see the blue line-Figure 11). If the height of the truss at the support changed to 1.9*m*, additional material saved. The red line-Figure 11 shows the optimization result and the weight is 16% less than the weight by manufacturer. The detailed optimization results of frame with H_{truss}=1.9*m* are shown in Figure 12 and Table 4.

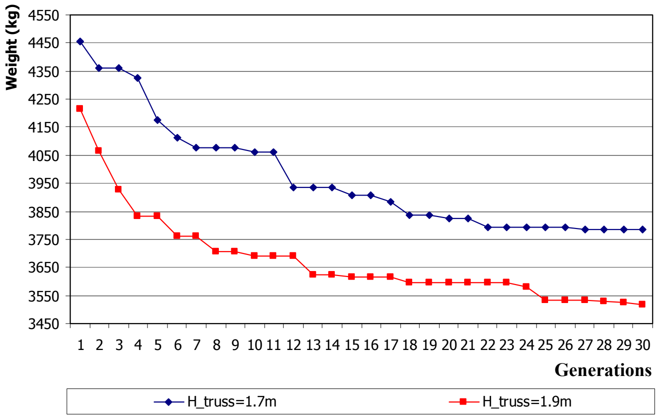

Figure 11: Optimization results with H_{truss}=1.7*m* and H_{truss}=1.9*m*

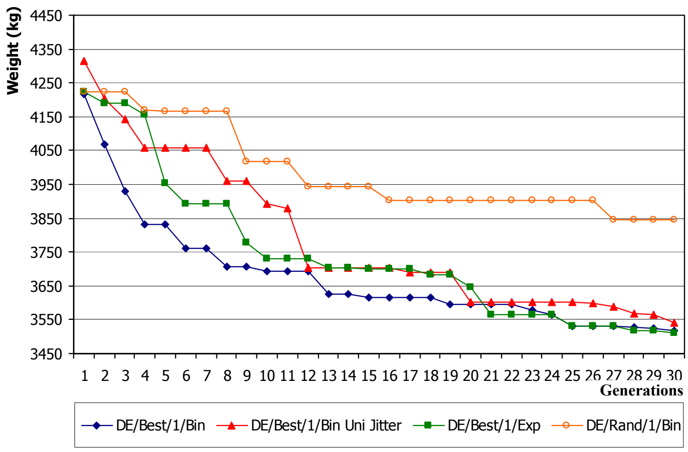

Figure 12: Optimization results of structure 3

Strategy	Weight (€)	Structure 3 (*kg*)	Percentage (%)
DE/Best/1/Bin	3517.4	4190.8	83.9
DE/Best/1/Exp	**3512.0**		**83.8**
DE/Rand/1/Bin	3844.6		91.7
DE/Best/1/Bin Uni Jitter	3541.4		84.5

Table 4: Optimization results of structure 3

These results indicate that the optimum weight obtained, using the DE-Algorithm, is approximately 16% better than the result designed by manufacturer. With the use of *DE/Best/1/Exp* strategy (Figure 12), the best result of optimal design is 3512.0*kg*, which means that the saving material is ca. 680*kg* per frame and approximately ca. 14.3*tons* for the whole building.

4 CONCLUSIONS

In comparison with the conventional design methods, the optimization-based design strategy with the DE-Algorithm has proved itself more efficient in reality. All optimized structures in Section 3 generated optimization solutions from 9% to 27%, corresponding to the design problems, better than the original solutions designed by experienced manufacturers.

All optimized frame structures whose columns and rafters used beam elements, are non-linearly analyzed according to the second-order-theory. The determination of the buckling moment resistance with consideration of lateral torsional buckling is relatively complicated because the coefficients which depend on the loading and end-restraint conditions are not easily determined. The use of similarly model structures using beam elements with the seventh degree of freedom which permits the calculation of torsional moment, shows the possibilities of analysis of this frame structure in reality.

Taking the criteria regarding the quality and efficiency of the design into consideration, the produced optimal design with the DE-Algorithm can completely replace traditional design because of the optimization results achieved above. It is proposed that civil engineers can apply the presented optimization program system with many design norms such as Eurocode (EC-3), German standard (DIN 18800) etc. in their practical designs of steel frame structures.

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