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Optimization of tubular trusses using intumescent coating in fire

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Summary. In steel structures, the cost of fire protection can be significant. They are typically designed to resist loads at room temperature after which the fire protection is considered. This widely used approach may result in expensive and unpractical solutions. On the other hand, automatic design systems utilizing optimization allow taking fire design aspects into account simultaneously. In this research, these two approaches are compared in a tubular roof truss case where intumescent coating is used as fire protection. The results show clearly the benefits of combined structural and fire engineering design. Design with Finnish national and ETA approvals of intumescent coating are compared for 30 and 60 minutes resistance to standard fire. It is shown, that ETA-approved rules indicate increased costs to tubular structures for 60 minutes fire. For 30 minutes the difference between the two approval systems were less significant.

Key words: tubular steel truss, optimization, fire, intumescent coating

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Introduction

Tubular welded trusses are widely used in buildings due to their aesthetically pleasing appearance, good load bearing capacity and cost effectiveness. An essential property of a truss is its fire resistance, because all buildings have to fulfill local fire regulations. The fire scenario is defined for each given project, and typically either ISO-834 fire or natural fire is employed. The resistance of the structure in fire can be accomplished without any additional protection, or by using either passive or active fire protection. These approaches can also be combined such that appropriate structural performance in fire is achieved by increasing the member sizes as well as applying fire protection. As different methods for attaining a suitable fire resistance are available, the designer is faced with the task of finding the most economical approach for the structure at hand.

The purpose of the present study is to assess the economy of welded single span tubular roof trusses under ISO-834 fire when intumescent paint is employed as fire protection (Fig. 1). Two design approaches are compared. The first approach emulates a ”conventional” engineering practice, where the truss is first designed in room temperature and the required paint thickness in fire conditions is determined in a second design phase. In the second approach, member sizing and determination of paint thickness are performed

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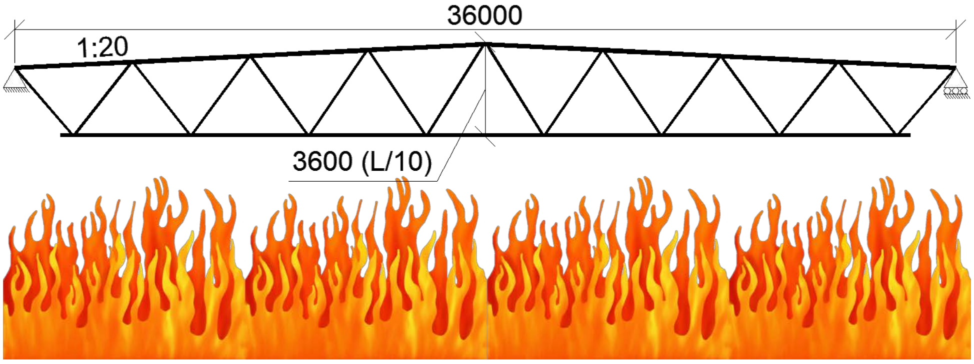

Figure 1. Considered case.

simultaneously such that the total cost of the truss is minimized. This more advanced approach relies on iterative optimization methods as finding the minimum cost design requires a compromise between minimizing the member sizes and minimizing the amount of paint.

The design of trusses is governed by the Eurocode EN 1993. For fire design, EN 1993-1-2 [5] is employed. The standard enables the use of various approaches for showing sufficient structural safety in fire conditions. In this study, the method of the critical temperature is adopted. The idea is to determine the (critical) temperature at which the structure collapses under the loads of fire situation. The paint producers provide tables that give the required intumescent coating thickness for given critical temperature at and cross-section section factor at specific time.

The method for the intumescent design in Finland is moving from nationally approved certified product declarations from the Finnish Constructional Steelwork Association (FCSA) to European Technical Approval (ETA) specifications. This affects the testing method and ultimately the required fire paint thickness. In this study, the ETA approved intumescent FIRETEX FX2002 is used [14]. This is compared with the older FIRETEX FX2000 which is approved by FCSA [2] in R30-R60 (valid until June 1st 2016). Requirements R30 and R60 mean that structure is supposed to withstand loads for 30 and 60 minutes, respectively, after the beginning of fire. As the range of validity and the thickness of the intumescent coating is different for the two approvals, it is interesting to examine the influence of the newer ETA system on the total cost of the truss, compared with the older FCSA approval. This comparison is included in the present study.

For minimizing the cost of the truss, the costs of the different fabrication phases need to be evaluated. Several methods for estimating the fabrication costs of steel structures have been presented in the literature [20, 11, 17, 15, 13, 7]. In this study, a feature-based costing method [8] adopted. The cost of material, blasting, sawing, welding, painting and intumescent painting are included in the cost function. The unit costs and fabrication times are estimated based on discussions with local workshops.

In order to minimize the costs, the truss design task must be formulated as a mathematical programming problem with clearly defined design variables, objective and constraints functions. The cost minimization problem of tubular trusses in fire conditions according to the Eurocode leads to a nonlinear discrete optimization problem where some of the functions are known only implicitly with respect to the design variables. For such problems, the variety of applicable solution methods is rather limited. In this study, a meta-heuristic population-based Particle Swarm Optimization (PSO) method is employed. This method has been found reliable for discrete truss optimization in previous

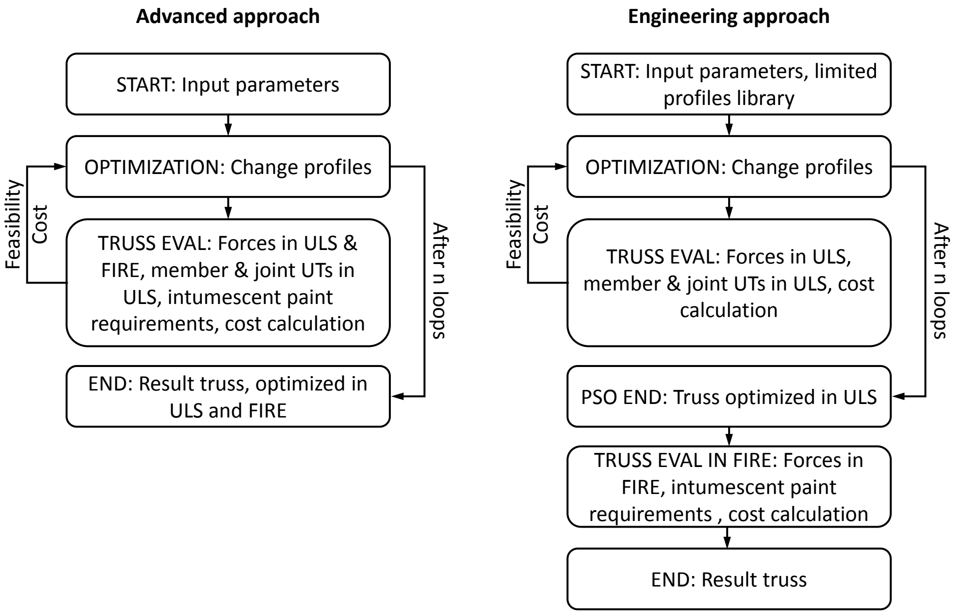

Figure 2. Advanced approach and engineering approach for truss design in fire conditions.

research [10].

The paper is organized as follows. Firstly, the two approaches for truss design in fire conditions considered in this study are described. Then, the cost optimization problem is presented, including details of structural modelling and design according to the Eurocode. The results of optimization are treated in detail, and finally, the implications of the study are discussed.

Tubular truss design in fire conditions

Designing trusses for fire safety using intumescent coating involves determining the member profiles and the thickness of the coating. The required amount of the fire paint depends on the dimensions of the cross-section. For tubular profiles, the key factor is the wall thickness, i.e. for thicker profiles, less paint is required. Consequently, the minimum cost design is a compromise between reducing the member sizes and the amount of intumescent paint. In general, this is not a simple task to be solved relying only on experience and engineering skills.

In this study, two approaches for truss design in fire conditions are considered. The first approach emulates a conventional engineering process, whereas in the second the cost minimization task is treated more comprehensively. In both approaches, the design is governed by the Eurocodes EN 1993-1-1 [4], EN 1993-1-8 [6] for members and joints in ambient conditions, and EN 1993-1-2 [5] for fire design. In this study, the recommended values of all parameters are used, i.e. no national annexes are employed.

The two approaches are schematically illustrated in Fig. 2.

Engineering approach

A typical design procedure is to first design the truss in ambient conditions (room temperature), and then to determine the required fire paint thickness for the obtained member profiles.

The design of the truss in ambient conditions is carried out by applying an optimization procedure. This emulates a seasoned engineer, who conventionally tries to find the most economical solution based on experience and judgment.

Advanced approach

It is clear the the engineering approach might lead to relatively thick intumescent coating, because the member profiles are made a small as possible in ambient conditions. In order to obtain more economical solution, sizing of the member profiles should be coupled with the determination of the coating thickness. The method of critical temperature is employed along with manufacturer's tables for finding the required intumescent paint thickness.

The minimum cost design is determined using a similar optimization procedure as for the engineering approach. The main difference is that now the cost of the intumescent paint is included in the cost function, whereas for the engineering approach, the cost of the paint is calculated only after the optimization has been terminated.

Cost minimization

Both approaches to truss design in fire conditions rely on optimization. Consequently, the truss design task must be formulated as an optimization problem, which includes the definition of design variables, objective function and constraints. This is described in the following along with details on structural modelling and fire design according to the Eurocode.

Structural modelling and design

For evaluating the performance of the truss in elevated temperature, structural analysis in fire conditions must be performed. The truss considered in this study is globally statically determinate truss of Fig. 1. Due to the structural analysis model used in this study the truss is internally statically indeterminate, but is has been shown that when the global support conditions are statically determinate, linear analysis predicts rather well the ultimate situation of the truss in fire [1]. This is especially true when dealing with the stress resultants of the truss.

The resistance of members and joints is verified in the Ultimate Limit State (ULS) in fire. The deflections are handled with pre-cambering, and they are not included in the analysis. The height of truss is $L/10$ ($L = 36\,\mathrm{m}$ is the span) at mid-span and it is measured from the bottom of the bottom chord to the top of the top chord. The slope of the top chord is 1:20. The truss consists of K-joints, with the gap of 50 mm at each joint. The joints are located evenly at the chords.

The design load in ambient conditions is a uniform load 23.5 kN/m at the top chord and in fire conditions the load is approximated as $0.4 \cdot 23.5\,\mathrm{kN/m}$.

The gaps and profile dimensions induce eccentricities at the joints, which cause secondary bending moments in the members. This is taken into account by introducing rigid eccentricity elements at the joints (Fig. 3). An eccentricity element is created between the mid-line of the chord and the intersection of the mid-lines of the connecting braces such that the element is perpendicular to the chord. The location of the nodes of the eccentricity element is calculated from the member profile dimensions, gap size and angles of the braces. Such structural model based on the accurate geometry is an important feature for

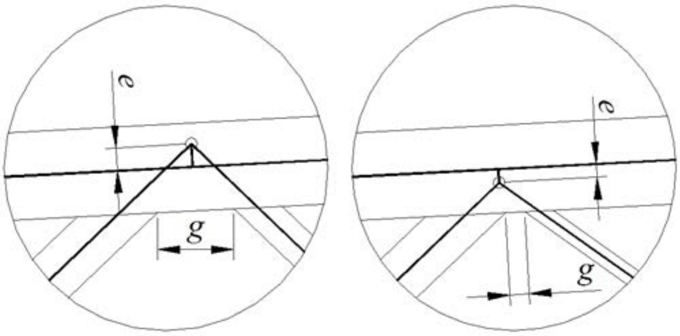

Figure 3. Local structural models of K-joints following EN 1993-1-8.

structural analysis and optimization according to the Eurocode, when the joint design is included in the procedure, because the details of the joints have an impact on the global structural model and therefore on the internal forces of the members.

The chords are modelled as continuous beams and diagonals are hinged at both ends. Euler-Bernoulli beam elements are used for the members and for the local models of the joints [10]. The buckling length of each member is 0.9 times the system length, which is defined as in [3], see also [9].

Fire design of members is performed using the method of critical temperatures of EN 1993-1-2 and calculating the minimum required intumescent thickness for each member. For compressed members the critical temperature is dependent on the elastic modulus temperature reduction in addition to yield strength reduction. This means that the critical temperature method is not directly applicable for compressed members, unless some iteration is performed. Three iterations for each compressed member proved to be sufficient to get the critical temperatures within 1°C accuracy.

The critical temperature $\theta_{\mathrm{a,cr}}$ (°C) is calculated as

$$\theta_{\mathrm{a,cr}} = 39.19 \cdot \ln\left(\frac{1}{0.9674\mu_0^{3.833}} - 1\right) + 482, \quad \mu_0 \geq 0.013 \tag{1}$$

where μ_0 is the degree of utilization of the member in fire. When the μ_0 of the member is known the critical temperature of the member can be calculated using Eq. (1). For square tubes the section factor value $A/V \approx 1/t$ can be used (see EN 1993-1-2). In this expression t is the wall thickness of the tube in meters. When the critical temperature $\theta_{\mathrm{a,cr}}$ and the section factor A/V are known the required intumescent cover thickness is retrieved from the tables of the coating fabricators.

The method for the intumescent design in Finland is moving from nationally approved certified product declarations from the Finnish Constructional Steelwork Association (FCSA) to European Technical Approval (ETA) specifications. This affects the testing method and ultimately the required fire paint thickness. In this study, the ETA approved intumescent FIRETEX FX2002 is used [14]. This is compared with the older FIRETEX FX2000 which is approved by FCSA [2] in R30-R60 (valid until June 1st 2016). Different calculation methods are employed for ETA and for FCSA. The ETA gives tables for paint thicknesses when critical temperatures are known and FCSA gives formulas for temperatures when the paint thickness is known. For a straightforward comparison, the intumescent coating thickness tables are calculated also for the FCSA tables using the same system as for the ETA, see Table 10 and Table 11. Neither FCSA product declarations nor ETA specifications give separate rules for profiles in tension, thus values for columns are used for all truss members. The paint thickness tables have values up to 5 mm, but in reality over 2 mm paint thicknesses often pose difficulties to transportation and installation. However, these practical limitations are not considered here.

If Table 10 and Table 11 are compared with the corresponding tables for FIRETEX FX2002 [14], it can be seen that the FCSA-approved values are valid for a wider range of section factors and temperatures. With lower critical temperatures or higher section factors the ETA produces significantly greater paint thicknesses. Alternatively, when the critical temperature is high and the section factor relatively low, the difference is quite small. For example, consider a tube with 8 mm wall thickness ($A/V \approx 125$) with 650 °C critical temperature in R60 fire. The required intumescent paint thickness is 0.986 mm with FCSA and 1.208 mm with ETA. For 5 mm wall thickness ($A/V \approx 200$), the corresponding values are 1.578 mm and 3.290 mm, respectively. These significant differences in required paint thicknesses probably originate from different paint testing methods used by FCSA and ETA, but the exact reasons have not yet been fully explored.

The method of the critical temperature is also applied to joint design in fire. The geometrical requirements for the joints are the same for ambient and fire conditions. The resistance checks of welded tubular K-joints includes checks for 7 failure modes with axial loads of the braces (Figure 7.3 of EN 1993-1-8): chord face failure, chord side wall failure, chord shear failure, punching shear failure, brace failure, local buckling of the brace, and local buckling of the chord. The resistance of the joint with respect to each failure mode is expressed as the allowable member axial force.

Denote by $N_{i,Ed}$ and $N_{i,Rd}$ the axial force and the resistance of brace i in ambient conditions, respectively. As linear structural analysis is performed, the axial force in fire conditions is $N_{i,Ed,t_0} = 0.40 N_{i,Ed}$. The resistance N_{i,Rd,t_0} is calculated at $t = 0$ for each member of the joint using the limiting failure mode acting on that member. The utilization ratios $\mu_0 = N_{i,Ed,t_0}/N_{i,Rd,t_0}$ can be then calculated for each member. The process is very much similar as in normal member fire design.

In this study, the gas temperature follows the ISO-834 standard curve. It is recognized by the authors that this choice places rather strict requirement for the structures. Switching to natural fire design could often produce much more economical structures regardless of the design approach used. However, as the scope of this paper is to compare the two design approaches rather than to find the most realistic fire scenario, the widely used ISO-834 curve is adopted.

Optimization

Sizing of the truss members is carried out by an optimization procedure, which requires a careful definition the corresponding optimization problem. In this study, the member profiles are taken as the discrete design variables. The profile catalogue is shown in Table 1. It consists of cold-formed square tubes fabricated by SSAB [18]. The objective is the fabrication cost of the truss, and the constraints are derived from EN 1993.

The fabrication costs include material, blasting, sawing, welding, painting and costs of the intumescent paint. The material cost for S420 steel is 1 €/kg, and the cost of the intumescent paint is 40 €/m^2 per 1 mm coating thickness. If the thickness of the coating is smaller or larger than 1 mm then the linear extrapolation is used. The amount of steel and the surface area to be painted are calculated using the exact geometrical form of the truss. Blasting, sawing and welding costs are calculated by a featured-based costing method [8].

Table 1. Catalogue of square hollow sections. The tube dimensions are given in form $h \times t$, where h is the outer dimension (width or height) in millimeters and t is the wall thickness in millimeters.

25x3	70x4	100x5	140x6	180x8
30x3	70x5	100x6	140x8	180x10
40x3	80x3	100x8	150x5	200x8
40x4	80x4	110x4	150x6	200x10
50x3	80x5	110x5	150x8	200x12.5
50x4	80x6	120x4	150x10	250x6
50x5	90x3	120x5	150x12.5	250x8
60x3	90x4	120x6	160x6	250x10
60x4	90x5	120x8	160x8	250x12.5
60x5	90x6	120x10	160x10	300x10
70x3	100x4	140x5	180x6	300x12.5

The numerical values of the different cost factors are very much dependent on the country, contractor and other issues. However, in order to compare different solutions these values must be estimated. In this study the costs mentioned above have been obtained from discussions with contractors in Finland. Transport and erection costs on site are not taken into account in this analysis, because they do not play an important role in this comparison. In the engineering approach the cost of the intumescent paint is not included in the objective function. The cost of fire protection is added to the other fabrication costs of the truss after optimization.

The constraints are derived from the Eurocodes. For members this implies axial force, shear force and bending moment resistances in ambient conditions. Flexural buckling and beam-column behaviour of compression members are taken into account using EN 1993-1-1, Method B. The corresponding resistances are also verified in fire conditions using EN 1993-1-2.

The K-joints (not at support and at the ridge) are checked in ambient conditions according to EN 1993-1-8 and in fire by EN 1993-1-2. The joint constraints include the joint resistance checks and the geometrical conditions which define the range of applicability of the resistance rules. Full strength welds are used at the joints. This implies that for S420 members, the weld size is $1.4t$ where t is the wall thickness of the connected brace. In fire condition the resistance of the welds is not considered. The details of the optimization problem can be found in [19].

Sizing optimization is performed using the metaheuristic Particle Swarm Optimization (PSO) method. PSO cannot guarantee the optimality of the solution, but with sufficiently large swarm size and using proper parameters, satisfactory results can be obtained. The details of PSO can be found in [12] and the applied constraint handling mechanism is described in [16]. The algorithm is run with the following key parameters: population size 250, iterations 120, number of runs 40.

In the engineering approach the truss is optimized in ambient conditions. To exclude impractically thin profiles for fire design, the minimum wall thickness of 5 mm is prescribed. This limitation is not needed in advanced approach due to the more holistic nature of the method.

After optimization, the required intumescent thicknesses are calculated using the critical temperatures for the members and for the joints. If the critical temperature and section factor combination is outside the range of the intumescent paint, the thickness

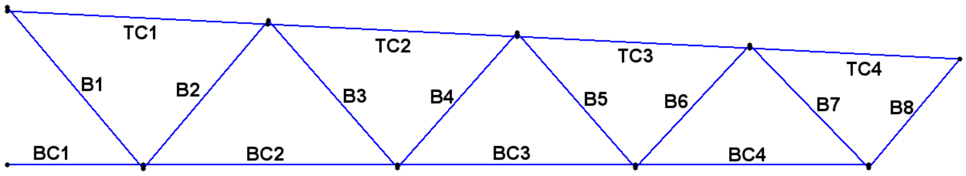

Figure 4. Member labels.

Table 2. Results of optimization. Best found member profiles. The member labels correspond to Fig. 4. TC and BC refer to top and bottom chords, respectively.

Method	Engineering				Advanced			
Paint	ETA		FCSA		ETA		FCSA	
Fire	R30	R60	R30	R60	R30	R60	R30	R60
TC	180x10	180x10	180x10	180x10	180x10	180x10	180x10	180x10
BC	120x8	120x8	120x8	120x8	120x8	150x10	120x8	120x10
B1	50x5	50x5	50x5	50x5	50x3	80x6	80x4	50x4
B2	70x5	70x5	70x5	70x5	70x3	80x6	70x4	80x4
B3	90x5	90x5	90x5	90x5	110x4	120x6	90x5	80x6
B4	70x5	70x5	70x5	70x5	80x3	100x6	70x4	70x5
B5	100x5	100x6	100x5	100x5	100x5	150x6	100x5	100x6
B6	70x5	70x5	70x5	70x5	70x4	100x6	70x4	80x6
B7	120x5	120x6	120x5	120x5	120x5	140x8	120x5	120x6
B8	90x5	90x5	90x5	90x5	90x4	120x6	90x6	80x6

of the member is increased for the next possible. Altogether four different intumescent coating thicknesses are allowed in the truss: one for the top chord, one for the bottom chord and two for the braces. This reflects the fact that at employing individual coating thicknesses at the workshop is time-consuming and prone to errors. In the engineering approach the grouping of the braces is done after the intumescent coating thickness is defined to all members separately. In the advanced approach this sorting is done during the optimization.

Results

The member profiles obtained by PSO are listed in Table 2 for different fire cases and for the two approaches described above. As can be expected, the profiles obtained by the engineering approach are nearly identical in all four cases. Only the braces B5 and B7 needed to be changed in R60 fire using ETA. In the advanced approach the member sizes vary considerably depending on the case. Only the top chord profile remains constant among the different cases.

The fire paint thicknesses for the optimized designs are shown in Table 3. For R30, the paint thicknesses are nearly identical for both approaches and ETA and FCSA tables. On the other hand, for R60, substantial differences can be observed. Using the advanced approach clearly leads to thinner coating, especially when ETA approval is adopted. For example, using the ETA approval, the engineering approach leads to paint thickness of 1.949 mm for the bottom chord, whereas only 0.506 mm layer is required when the advanced approach is utilized. Similar ratio applies for the braces as well, but for the

Table 3. Fire paint thicknesses (mm).

Method	Engineering				Advanced			
Paint	ETA		FCSA		ETA		FCSA	
Fire	R30	R60	R30	R60	R30	R60	R30	R60
Top Chord	0.462	0.980	0.325	0.885	0.462	0.987	0.325	0.885
Bottom Chord	0.462	1.949	0.427	1.166	0.462	0.506	0.427	0.879
B1	0.462	2.846	0.500	1.494	0.462	1.062	0.435	1.091
B2	0.462	2.846	0.500	1.494	0.462	1.062	0.435	1.091
B3	0.462	3.813	0.742	1.968	0.462	0.768	0.742	1.584
B4	0.462	2.846	0.500	1.494	0.462	0.768	0.435	1.091
B5	0.522	3.813	0.742	1.968	0.523	0.768	0.742	1.584
B6	0.522	2.846	0.500	1.494	0.523	0.768	0.742	1.091
B7	0.522	3.813	0.742	1.968	0.523	1.062	0.742	1.584
B8	0.522	3.813	0.742	1.968	0.523	1.062	0.435	1.584

Table 4. Minimum costs, the corresponding weights and costs distributions.

Method	Engineering				Advanced			
Paint	ETA		FCSA		ETA		FCSA	
Fire	R30	R60	R30	R60	R30	R60	R30	R60
Weight (kg)	1651	1670	1651	1651	1607	2105	1650	1764
Cost (€)	2569	4273	2543	3411	2499	3746	2534	3327
Material	1651	1670	1651	1651	1607	2105	1650	1764
Welding	146	165	146	146	108	297	139	176
Sawing	97	98	97	97	97	103	97	97
Blasting	22	22	22	22	22	22	22	22
Painting	128	127	128	128	130	147	130	127
Fire Paint	525	2191	499	1367	535	1071	496	1140

top chord, the paint thickness is virtually identical for both approaches. When the paint thickness is determined according to FCSA, the difference between the two approaches is smaller. The engineering approach leads to 25–36% greater paint thickness, except for the top chord.

The costs and weights of the obtained designs are given in Table 4. The advanced approach leads to slightly more economical designs with ETA in R30 and FCSA in R60. There is practically no difference in cost using FCSA in R30. However, in R60 with ETA, the advanced approach gives 12 % from the solution obtained by the engineering approach. Note that in this case, the weight of the more economical solution is 26% greater than the weight of the less economical design.

The cost distributions of the solutions, shown in Table 4, illustrate the fact that in R60 the cost of the intumescent coating can be as great as (or greater than) the cost of steel when engineering approach is employed. Using the advanced approach the cost of the fire paint is always smaller than the material cost. Note that with the adopted unit costs, the cost of fire paint is greater than the other fabrication costs combined.

Table 5. Utilities of members with respect to the resistances.

Method	Engineering				Advanced			
Paint	ETA		FCSA		ETA		FCSA	
Fire	R30	R60	R30	R60	R30	R60	R30	R60
B1	0.01	0.01	0.01	0.01	0.01	0	0	0.01
B2	0.01	0.01	0.01	0.01	0	0.01	0.01	0.01
B3	0.60	0.60	0.60	0.60	0.43	0.25	0.60	0.73
B4	0.26	0.26	0.26	0.26	0.36	0.15	0.32	0.26
B5	0.89	0.77	0.89	0.89	0.89	0.31	0.89	0.77
B6	0.58	0.58	0.58	0.58	0.70	0.33	0.70	0.42
B7	0.93	0.80	0.93	0.93	0.93	0.46	0.93	0.80
B8	0.71	0.71	0.71	0.71	0.86	0.44	0.60	0.69
TC1	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
TC2	0.82	0.81	0.82	0.82	0.81	0.82	0.82	0.81
TC3	0.64	0.63	0.64	0.64	0.63	0.63	0.63	0.63
TC4	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
BC1	0.80	0.80	0.80	0.80	0.79	0.52	0.80	0.66
BC2	0.87	0.87	0.87	0.87	0.89	0.56	0.87	0.72
BC3	0.72	0.72	0.72	0.72	0.73	0.49	0.72	0.61
BC4	0.99	0.99	0.99	0.99	0.99	0.59	0.99	0.80

In order to evaluate the performance of PSO in this problem the utilization ratios of members and joints with respect to the resistances are given in Table 5 and Table 6. The "utilities" with respect to the geometrical properties of the joints are given in Table 7, and the maximum utilization ratios for all members, including member and joint resistances and the geometrical "utilities" are given in Table 8. It can be seen, that very high utilization ratios (values near 1.00) are obtained in all cases, which implies excellent performance of the designs.

The sensitivity of the solutions with respect to the initial cost data is examined by re-optimizing the structures using the steel material cost 0.8 €/kg instead of 1.0 €/kg. The obtained costs and the corresponding weights are given in Table 9.

Table 6. Utilities of joints with respect to the resistance.

Method	Engineering				Advanced			
Paint	ETA		FCSA		ETA		FCSA	
Fire	R30	R60	R30	R60	R30	R60	R30	R60
B1-BC-B2	0.88	0.88	0.88	0.88	0.88	0.57	0.88	0.73
B2-TC-B3	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
B3-BC-B4	0.89	0.89	0.89	0.89	0.89	0.57	0.89	0.74
B4-TC-B5	0.58	0.59	0.58	0.58	0.53	0.44	0.58	0.6
B5-BC-B6	0.82	0.82	0.82	0.82	0.82	0.52	0.82	0.66
B6-TC-B7	0.81	0.81	0.81	0.81	0.81	0.58	0.82	0.75
B7-BC-B8	0.95	0.95	0.95	0.95	0.95	0.5	0.95	0.79

Table 7. "Utilities" of geometrical constraints at joints.

Method	Engineering				Advanced			
Paint	ETA		FCSA		ETA		FCSA	
Fire	R30	R60	R30	R60	R30	R60	R30	R60
B1-BC-B2	0.84	0.84	0.84	0.84	0.84	0.70	0.74	0.84
B2-TC-B3	1.00	1.00	1.00	1.00	0.90	0.90	1.00	1.00
B3-BC-B4	0.83	0.83	0.83	0.83	0.92	0.83	0.83	0.74
B4-TC-B5	0.95	0.95	0.95	0.95	0.90	0.83	0.95	0.95
B5-BC-B6	0.95	0.95	0.95	0.95	0.95	1.00	0.95	0.90
B6-TC-B7	0.90	0.90	0.90	0.90	0.90	0.78	0.90	0.80
B7-BC-B8	1.00	1.00	1.00	1.00	1.00	0.93	1.00	1.00

Table 8. Combined utilities.

Method	Engineering				Advanced			
Paint	ETA		FCSA		ETA		FCSA	
Fire	R30	R60	R30	R60	R30	R60	R30	R60
B1	0.88	0.88	0.88	0.88	0.88	0.70	0.88	0.84
B2	1.00	1.00	1.00	1.00	0.90	0.90	1.00	1.00
B3	1.00	1.00	1.00	1.00	0.92	0.90	1.00	1.00
B4	0.95	0.95	0.95	0.95	0.92	0.83	0.95	0.95
B5	0.95	0.95	0.95	0.95	0.95	1.00	0.95	0.95
B6	0.95	0.95	0.95	0.95	0.95	1.00	0.95	0.90
B7	1.00	1.00	1.00	1.00	1.00	0.93	1.00	1.00
B8	1.00	1.00	1.00	1.00	1.00	0.93	1.00	1.00
TC1	1.00	1.00	1.00	1.00	0.90	0.90	1.00	1.00
TC2	1.00	1.00	1.00	1.00	0.90	0.90	1.00	1.00
TC3	0.95	0.95	0.95	0.95	0.90	0.83	0.95	0.95
TC4	0.90	0.90	0.90	0.90	0.90	0.78	0.90	0.80
BC1	0.88	0.88	0.88	0.88	0.88	0.70	0.88	0.84
BC2	0.89	0.89	0.89	0.89	0.92	0.83	0.89	0.84
BC3	0.95	0.95	0.95	0.95	0.95	1.00	0.95	0.90
BC4	1.00	1.00	1.00	1.00	1.00	0.93	1.00	1.00

As the material unit cost is decreased, the advanced approach leads to greater savings than in the first scenario, where the unit cost of steel was 1.0 €/kg. Using ETA in R60, the advanced approach gives 23 % more economical design than the engineering approach. For the other cases, from 4 % to 8 % savings can be achieved by the advanced approach.

Conclusions

The findings of the present study indicate that the proposed "advanced approach" should be employed in fire design of tubular trusses in all cases. Especially when the fire resistance requirement is high traditional method of finding the least weight solution does not seem to produce the most economical solution. The single drawback of the advanced approach

Table 9. Costs and weights of optimal cases using the steel material cost 0.8 €/kg.

Method	Engineering				Advanced			
Paint	ETA		FCSA		ETA		FCSA	
Fire	R30	R60	R30	R60	R30	R60	R30	R60
Cost (€)	2317	4303	2292	3286	2197	3315	2210	3020
Weight (kg)	1630	1640	1630	1630	1619	1977	1643	1824

is that it requires unit costs for steel, intumescent paint and other fabrication phases. In order to provide the designer with the best possible tools for finding the most economical structures, the authors recommend that the workshops and steel producers make this data available. This can be done, for example, in a closed design software, that enables cost optimization but does not reveal all sensitive cost data.

In this study the particle swarm optimization method was employed, but the automated member sizing can be performed by other means as well, including sophisticated mathematical programming methods, and ad hoc engineering rules. The most important feature of advanced approach is the combined sizing and intumescent paint thickness determination which are done simultaneously in order to find the most economical designs.

Finally, it should be noted that it is the experience of the authors that the discrete optimization problem resulting from detailed structural modelling and constraints derived from the Eurocode is very difficult to solve, and possibly a combination of heuristic methods and mathematical programming algorithms leads to a suitable solution strategy.

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References

[1] J.A. Diez Albero, T. Tiainen, K. Mela, and M. Heinisuo. Structural analysis of tubular trusses in fire. In E. Batista, P. Vellasco, and L. Lima, editors, *Tubular Structures XV*, Rio de Janeiro, Brazil, May 2015. Proceedings of the 15th international symposium on tubular structures.

[2] Finnish Constructional Steel Association. *Varmennettu Käyttöseloste TRY-107-2011: FIRETEX FX2000 -palosuojamaali putki- ja I-profiilien palosuojaukseen.* Finnish Constructional Steel Association, 2011. In Finnish.

[3] H. Boel. Buckling length factors of hollow section members in lattice girders. Master's thesis, Eindhoven University of Technology, 2010.

[4] EN 1993–1–1. *Eurocode 3: Design of Steel Structures. Part 1-1: General rules and rules for buildings.* CEN, 2005.

[5] EN 1993–1–2. *Eurocode 3: Design of Steel Structures. Part 1-2: General rules – Structural fire design.* CEN, 2005.

[6] EN 1993–1–8. *Eurocode 3: Design of Steel Structures. Part 1-8: Design of joints.* CEN, 2005.

[7] J. Farkas and K. Jármai, editors. *Optimum Design of Steel Structures.* Springer, 2013.

[8] J. Haapio. *Feature-Based Costing Method for Skeletal Steel Structures Based on the Process Approach.* PhD thesis, Tampere University of Technology, 2012.

[9] M. Heinisuo and Ä. Haakana. Buckling of members of welded tubular truss. In Markku Heinisuo and Jari Mäkinen, editors, *Proceedings of The 13th Nordic Steel Construction Conference (NSCC-2015)*, pages 23–25, Tampere, Finland, sep 2015.

[10] J. Jalkanen. *Tubular Truss Optimization Using Heuristic Algorithms.* PhD thesis, Tampere University of Technology, 2007.

[11] K. Jármai and J. Farkas. Cost calculation and optimisation of welded steel structures. *Journal of Constructional Steel Research*, 50:115–135, 1999. doi:10.1016/S0143-974X(98)00241-7.

[12] J. Kennedy and R. Eberhart. Particle swarm optimization. In *IEEE International Conference on Neural Networks*, pages 1942–1948, 1995.

[13] U. Klanšek and S. Kravanja. Cost estimation, optimization and competitiveness of different composite floor systems–part 1: Self-manufacturing cost estimation of composite and steel structures. *Journal of Constructional Steel Research*, 62:434–448, 2006. doi:10.1016/j.jcsr.2005.08.005.

[14] Warrington Certification LTD. *European technical approval ETA-12/0049: FIRETEX FX2002 and FIRETEX FX1002.* EOTA, Warrington, UK, 2013.

[15] L. Pavlovčič, A. Krajnc, and D. Beg. Cost function analysis in the structural optimization of steel frames. *Structural and Multidisciplinary Optimization*, 28:286–295, 2004. doi:10.1007/s00158-004-0430-z.

[16] G.T. Pulido and C.A.C. Coello. A constraint-handling mechanism for particle swarm optimization. In *Congress on Evolutionary Computation*, volume 2, pages 1396 – 1403, june 2004. doi:10.1109/CEC.2004.1331060.

[17] K. C. Sarma and H. Adeli. Cost optimization of steel structures. *Engineering Optimization*, 32:777–802, 2000. doi:10.1080/03052150008941321.

[18] SSAB. *Structural Hollow Section*, 2016. Dimensions and cross-sectional properties.

[19] T. Tiainen, K. Mela, and M. Heinisuo. High strength steel in tubular trusses. *Structures and Buildings*, 2016. Submitted.

[20] K.B. Watson, S. Dallas, N. Van der Kreek, and T. Main. Costing of steelwork from feasibility through to completion. *Journal of Australian Steel Construction*, 30(2):9, 1996.

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Appendix: FIRETEX FX2000 coating thickness tables

The coating thickness values are calculated using procedure described in [2]. The unit system in the Tables is: Intumescent thickness [mm], Critical temperature T[°C], Section factor A/V [1/m].

Table 10. FIRETEX FX2000, RHS, R30.

T A/V	350	400	450	500	550	600	650	700	750	800	850
70	0.759	0.558	0.431	0.346	0.300	0.300	0.300	0.300	0.300	0.300	0.300
75	0.813	0.598	0.462	0.371	0.305	0.300	0.300	0.300	0.300	0.300	0.300
80	0.867	0.638	0.493	0.396	0.326	0.300	0.300	0.300	0.300	0.300	0.300
85	0.921	0.678	0.523	0.421	0.346	0.300	0.300	0.300	0.300	0.300	0.300
90	0.976	0.718	0.554	0.445	0.366	0.304	0.300	0.300	0.300	0.300	0.300
95	1.030	0.757	0.585	0.470	0.387	0.321	0.300	0.300	0.300	0.300	0.300
100	1.084	0.797	0.616	0.495	0.407	0.338	0.300	0.300	0.300	0.300	0.300
105	1.138	0.837	0.647	0.520	0.427	0.354	0.300	0.300	0.300	0.300	0.300
110	1.192	0.877	0.677	0.544	0.448	0.371	0.307	0.300	0.300	0.300	0.300
115	1.247	0.917	0.708	0.569	0.468	0.388	0.321	0.300	0.300	0.300	0.300
120	1.301	0.957	0.739	0.594	0.489	0.405	0.335	0.300	0.300	0.300	0.300
125	1.355	0.997	0.770	0.619	0.509	0.422	0.349	0.300	0.300	0.300	0.300
130	1.409	1.037	0.801	0.643	0.529	0.439	0.363	0.300	0.300	0.300	0.300
135	1.463	1.076	0.831	0.668	0.550	0.456	0.376	0.306	0.300	0.300	0.300
140	1.518	1.116	0.862	0.693	0.570	0.473	0.390	0.318	0.300	0.300	0.300
145	1.572	1.156	0.893	0.717	0.590	0.489	0.404	0.329	0.300	0.300	0.300
150	1.626	1.196	0.924	0.742	0.611	0.506	0.418	0.341	0.300	0.300	0.300
155	1.680	1.236	0.955	0.767	0.631	0.523	0.432	0.352	0.300	0.300	0.300
160	1.734	1.276	0.985	0.792	0.651	0.540	0.446	0.363	0.300	0.300	0.300
165	1.789	1.316	1.016	0.816	0.672	0.557	0.460	0.375	0.300	0.300	0.300
170	1.843	1.355	1.047	0.841	0.692	0.574	0.474	0.386	0.300	0.300	0.300
175	1.897	1.395	1.078	0.866	0.712	0.591	0.488	0.397	0.309	0.300	0.300
180	1.951	1.435	1.109	0.891	0.733	0.608	0.502	0.409	0.318	0.300	0.300
185	2.005	1.475	1.139	0.915	0.753	0.624	0.516	0.420	0.327	0.300	0.300
190	2.060	1.515	1.170	0.940	0.774	0.641	0.530	0.431	0.336	0.300	0.300
195	2.114	1.555	1.201	0.965	0.794	0.658	0.544	0.443	0.345	0.300	0.300
200	2.168	1.595	1.232	0.990	0.814	0.675	0.558	0.454	0.353	0.300	0.300
205	2.222	1.635	1.263	1.014	0.835	0.692	0.572	0.465	0.362	0.300	0.300
210	2.276	1.674	1.293	1.039	0.855	0.709	0.586	0.477	0.371	0.300	0.300
215	2.331	1.714	1.324	1.064	0.875	0.726	0.600	0.488	0.380	0.300	0.300
220	2.385	1.754	1.355	1.089	0.896	0.743	0.614	0.499	0.389	0.300	0.300
225	2.439	1.794	1.386	1.113	0.916	0.759	0.627	0.511	0.398	0.300	0.300
230	2.493	1.834	1.417	1.138	0.936	0.776	0.641	0.522	0.406	0.300	0.300
235	2.547	1.874	1.447	1.163	0.957	0.793	0.655	0.533	0.415	0.300	0.300
240	2.602	1.914	1.478	1.188	0.977	0.810	0.669	0.545	0.424	0.300	0.300
245	2.656	1.953	1.509	1.212	0.997	0.827	0.683	0.556	0.433	0.300	0.300
250	2.710	1.993	1.540	1.237	1.018	0.844	0.697	0.568	0.442	0.300	0.300
255	2.764	2.033	1.570	1.262	1.038	0.861	0.711	0.579	0.451	0.300	0.300
260	2.818	2.073	1.601	1.286	1.059	0.878	0.725	0.590	0.460	0.306	0.300
265	2.873	2.113	1.632	1.311	1.079	0.894	0.739	0.602	0.468	0.312	0.300
270	2.927	2.153	1.663	1.336	1.099	0.911	0.753	0.613	0.477	0.318	0.300
275	2.981	2.193	1.694	1.361	1.120	0.928	0.767	0.624	0.486	0.323	0.300
280		2.233	1.724	1.385	1.140	0.945	0.781	0.636	0.495	0.329	0.300
285		2.272	1.755	1.410	1.160	0.962	0.795	0.647	0.504	0.335	0.300
290		2.312	1.786	1.435	1.181	0.979	0.809	0.658	0.513	0.341	0.300
295		2.352	1.817	1.460	1.201	0.996	0.823	0.670	0.521	0.347	0.300
300		2.392	1.848	1.484	1.221	1.013	0.837	0.681	0.530	0.353	0.300

Table 11. FIRETEX FX2000, RHS, R60.

T A/V	350	400	450	500	550	600	650	700	750	800	850
70	1.465	1.187	0.993	0.847	0.730	0.634	0.552	0.479	0.409	0.339	0.300
75	1.569	1.272	1.064	0.908	0.782	0.679	0.592	0.513	0.438	0.363	0.300
80	1.674	1.357	1.135	0.968	0.835	0.725	0.631	0.547	0.467	0.387	0.305
85	1.778	1.442	1.206	1.029	0.887	0.770	0.671	0.581	0.496	0.412	0.324
90	1.883	1.526	1.277	1.089	0.939	0.815	0.710	0.616	0.526	0.436	0.343
95	1.988	1.611	1.348	1.150	0.991	0.861	0.750	0.650	0.555	0.460	0.362
100	2.092	1.696	1.419	1.210	1.043	0.906	0.789	0.684	0.584	0.484	0.381
105	2.197	1.781	1.490	1.271	1.095	0.951	0.829	0.718	0.613	0.509	0.400
110	2.302	1.866	1.561	1.331	1.148	0.997	0.868	0.753	0.642	0.533	0.419
115	2.406	1.950	1.632	1.392	1.200	1.042	0.907	0.787	0.672	0.557	0.439
120	2.511	2.035	1.703	1.452	1.252	1.087	0.947	0.821	0.701	0.581	0.458
125	2.615	2.120	1.774	1.513	1.304	1.132	0.986	0.855	0.730	0.605	0.477
130	2.720	2.205	1.845	1.573	1.356	1.178	1.026	0.889	0.759	0.630	0.496
135	2.825	2.290	1.916	1.634	1.408	1.223	1.065	0.924	0.788	0.654	0.515
140	2.929	2.374	1.987	1.694	1.461	1.268	1.105	0.958	0.818	0.678	0.534
145		2.459	2.058	1.755	1.513	1.314	1.144	0.992	0.847	0.702	0.553
150		2.544	2.129	1.815	1.565	1.359	1.184	1.026	0.876	0.726	0.572
155		2.629	2.200	1.876	1.617	1.404	1.223	1.060	0.905	0.751	0.591
160		2.713	2.271	1.936	1.669	1.450	1.263	1.095	0.934	0.775	0.610
165		2.798	2.342	1.997	1.721	1.495	1.302	1.129	0.964	0.799	0.629
170		2.883	2.413	2.057	1.774	1.540	1.341	1.163	0.993	0.823	0.648
175		2.968	2.484	2.118	1.826	1.585	1.381	1.197	1.022	0.848	0.667
180			2.555	2.178	1.878	1.631	1.420	1.231	1.051	0.872	0.686
185			2.626	2.239	1.930	1.676	1.460	1.266	1.081	0.896	0.705
190			2.697	2.299	1.982	1.721	1.499	1.300	1.110	0.920	0.724
195			2.768	2.360	2.034	1.767	1.539	1.334	1.139	0.944	0.744
200			2.839	2.420	2.087	1.812	1.578	1.368	1.168	0.969	0.763
205			2.910	2.481	2.139	1.857	1.618	1.402	1.197	0.993	0.782
210			2.981	2.541	2.191	1.903	1.657	1.437	1.227	1.017	0.801
215				2.602	2.243	1.948	1.697	1.471	1.256	1.041	0.820
220				2.662	2.295	1.993	1.736	1.505	1.285	1.065	0.839
225				2.723	2.347	2.038	1.775	1.539	1.314	1.090	0.858
230				2.784	2.399	2.084	1.815	1.573	1.343	1.114	0.877
235				2.844	2.452	2.129	1.854	1.608	1.373	1.138	0.896
240				2.905	2.504	2.174	1.894	1.642	1.402	1.162	0.915
245				2.965	2.556	2.220	1.933	1.676	1.431	1.187	0.934
250					2.608	2.265	1.973	1.710	1.460	1.211	0.953
255					2.660	2.310	2.012	1.744	1.489	1.235	0.972
260					2.712	2.356	2.052	1.779	1.519	1.259	0.991
265					2.765	2.401	2.091	1.813	1.548	1.283	1.010
270					2.817	2.446	2.131	1.847	1.577	1.308	1.029
275					2.869	2.491	2.170	1.881	1.606	1.332	1.049
280					2.921	2.537	2.209	1.915	1.635	1.356	1.068
285					2.973	2.582	2.249	1.950	1.665	1.380	1.087
290						2.627	2.288	1.984	1.694	1.404	1.106
295						2.673	2.328	2.018	1.723	1.429	1.125
300						2.718	2.367	2.052	1.752	1.453	1.144