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SESSION NINE

SHAPE OPTIMIZATION TECHNIQUES

OPTIMUM DESIGN OF WELDED STEEL STRUCTURES

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ABSTRACT

In order to minimize the cost of welded structures, optimization studies should be performed, which need mathematical formulation of the cost function. The economy of welded structures plays an important role in the research and production. In structural optimization the version is sought which minimizes the objective function and fulfils the design constraints. As objective function the mass (weight) is often defined, but the minimum weight design does not give the optimal version for minimum cost. Therefore a more complex cost function should be defined including not only the material but also the fabrication costs. The manufacturing times are very good for computing the different costs at different countries and to compare the structural sizes. Multiobjective optimization techniques are useful for finding the compromize solutions, taking account several objectives. Artificial Intelligence techniques are the best utilized in identifying and evaluating design alternatives and there relevant constraints while leaving the important design decisions to the human.

KEYWORDS

Fabrication cost, minimum cost design, welded structural parts, welded box girders, stiffened plates, multiobjective optimization, expert systems.

1. INTRODUCTION

Optimum design is a structural synthesis which collects all important engineering aspects to work out safe and economic structural versions. The economy is achieved by minimizing the cost or weight function while the safety is guaranteed by fulfilling the design constraints on static stress, fatigue, stability, vibration, deflection, technological requirements, etc. We apply this cost calculation for design of box girders and stiffened plates. Expert system shells, the Personal Consultant and the LEVEL 5 OBJECT are used. The connection of the optimization techniques and the expert shells make it possible to find the best solution among several alternatives. The Rosenbrock Hillclimb procedure is used at LEVEL 5 OBJECT and five single-objective and seven multiobjective optimization techniques are used at Personal Consultant. We show the benefits of these systems in the optimum design of main girders of overhead travelling cranes. At the example the double crane girders are welded and stiffened box ones, with one trolley on it. We've used the British Standard for the structural analysis.

2. FABRICATION COST FUNCTIONS

The cost of a structure is the sum of the material and fabrication costs. The fabrication cost elements are the welding-, cutting-, preparation-, assembly-, tacking-, painting costs etc. It is very difficult to obtain such cost factors, which are valid all over the world, because there are great differences between the cost factors at the highly developed and developing countries. If we choose the time, as the basic data of a fabrication element we can handle this problem. The fabrication time depends on the technological level of the country and the manufacturer, but it is much closer to the real process to calculate with. After computing the necessary time for a fabrication work element one can multiply by a specific cost factor, which can represent the development level differences. Although the whole production cost depends on many parameters and it is very difficult to express their effect mathematically, a simplified cost function can serve as a suitable tool for comparisons useful for designers and manufacturers.

The cost function can be expressed as

$$K = K_m + K_f = k_m V + k_f \sum_i T_i \tag{1}$$

where K_m and K_f are the material and fabrication costs, respectively, k_m and k_f are the corresponding cost factors, ρ is the material density, V is the volume of the structure, T_i are the production times.

2.1. Fabrication times for welding

Eq.(1) can be written in the following form

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m}(T_1 + T_2 + T_3) \tag{2}$$

where

$$T_1 = C_1 \delta_d \sqrt{\kappa \rho V} \tag{3}$$

is the time for preparation, assembly and tacking, δ_d is a difficulty factor, κ is the number of structural elements to be assembled.

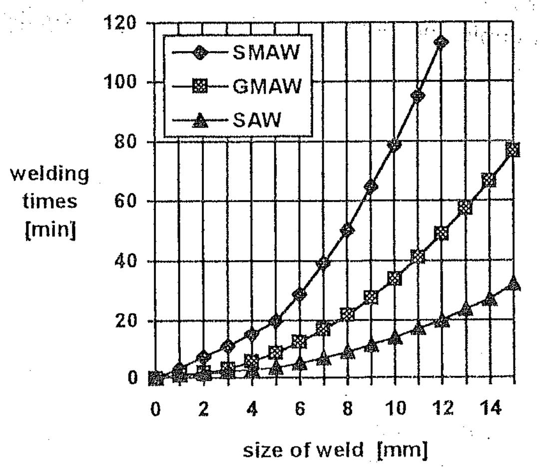

Fig. 1 Welding times for fillet welds of size a_w

$$T_2 = \sum_i C_{2i} a_{wi}^n L_{wi} \tag{4}$$

is the time of welding, a_{wi} is the weld size, L_{wi} is the weld length, C_{2i} and n are constants given for different welding technologies.

$$T_3 = \sum_i C_{3i} a_{wi}^n L_{wi} \tag{5}$$

is the time of additional fabrication actions such as changing the electrode, deslagging and chipping.

The different welding technologies are as follows:

SMAW, Shielded Metal Arc Welding, GMAW-C, Gas Metal Arc Welding with CO_2, SAW, Submerged Arc Welding

Table 1. Welding times T_2 (min) in function of weld size a_w (mm) for longitudinal fillet welds downhand position (see also Fig. 1.)

Welding method	a_w (mm)	$10^3 T_2 = 10^3 C_2 a_w^n$
SMAW	2 - 5	4.0 a_w
	5 - 15	0.786 a_w^2
GMAW-C	2 - 5	1.70 a_w
	5 - 15	0.339 a_w^2
SAW	2 -5	1.190 a_w
	5 - 15	0.236 a_w^2

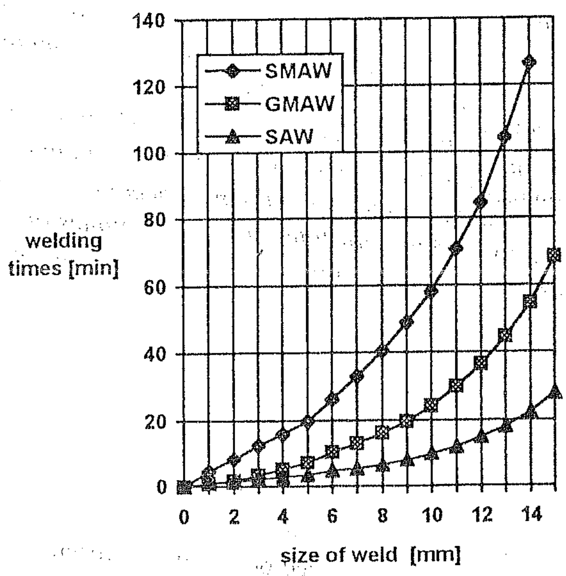

Fig. 2. Welding times for 1/2 V butt welds of size a_w

Table 2. Welding times T_2 (min) in function of weld size a_w (mm) for longitudinal 1/2 V butt welds downhand position (see also Fig. 2.)

Welding method	a_w (mm)	$10^3 T_2 = 10^3 C_2 a_w^n$
SMAW	2 - 5	$3.86\ a_w$
	5 - 15	$1.139\ a_w^{1.758}$
GMAW-C	2 - 5	$1.26\ a_w$
	5 - 15	$0.144\ a_w^{2.348}$
SAW	2 -5	$0.52\ a_w$
	5 - 15	$0.178\ a_w^2$

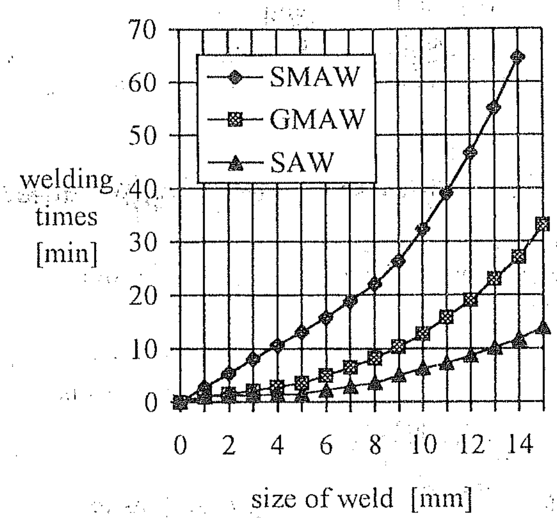

Fig. 3. Welding times for V butt welds of size a_w

Table 3. Welding times T_2 (min) in function of weld size a_w (mm) for longitudinal V butt welds downhand position (see also Fig. 3.)

Welding method	a_w (mm)	$10^3 T_2 = 10^3 C_2 a_w^n$
SMAW	2 - 5	$2.88\ a_w$
	5 - 15	$0.319\ a_w^2$
GMAW-C	2 - 5	$0.72\ a_w$
	5 - 15	$0.138\ a_w^2$
SAW	2 -5	$0.30\ a_w$
	5 - 15	$0.096\ a_w^2$

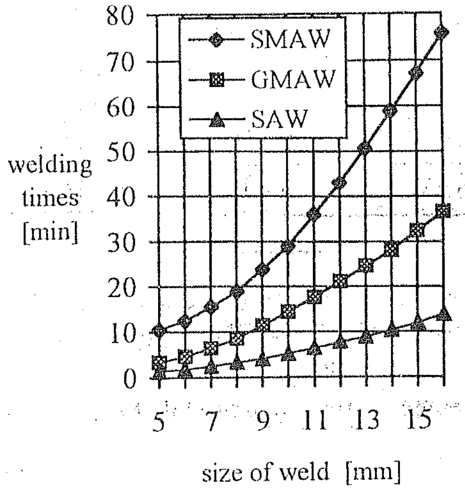

Fig. 4. Welding times for K-butt welds of size a_w

Table 4. Welding times T_2 (min) in function of weld size a_w (mm) for longitudinal K-butt welds downhand position (see also Fig. 4.)

Welding method	a_w (mm)	$10^3 t_2 = 10^3 C_2 a_w^n$
SMAW	5 - 16	$1.4029\ a_w^{1.25}$
GMAW-C	5 - 16	$0.129\ a_w^2$
SAW	5 - 16	$0.089\ a_w^2$

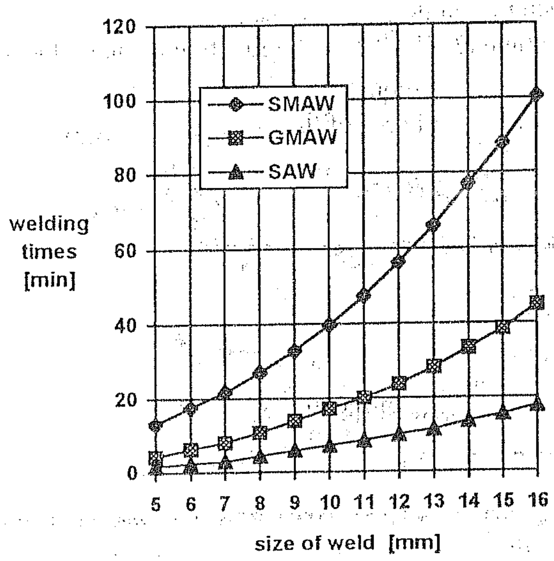

Fig. 5. Welding times for X-butt welds of size a_w

Table 5. Welding times T_2 (min) in function of weld size a_W (mm) for longitudinal X-butt welds downhand position (see also Fig. 5.)

Welding method	a_W (mm)	$10^3 T_2 = 10^3 C_2 a_w^n$
SMAW	5 - 16	$0.488 a_w^2$
GMAW-C	5 - 16	$0.169\ a_w^2$
SAW	5 - 16	$0.116\ a_w^2$

Ott and Hubka (1985) proposed that $C_{3i} = 0.3\ C_{2i}$, so

$$T_2 + T_3 = 1.3 \sum_i C_{2i} a_{wi}^n L_{wi} \tag{6}$$

Values of C_{2i} and n may be given according to *COSTCOMP* (1990) as follows. The COSTCOMP software gives welding times and costs for different technologies (Bodt 1990). To compare the costs of different welding methods and to show the advantages of automation, the manual SMAW, semi-automatic GMAW-C and automatic SAW methods are selected for fillet welds. The analysis of COSTCOMP data resulted in constants given in Fig. 1-5 and Table 1-5 for different joint types. It should be noted that in values for SAW a multiplying factor of 1.7 is considered since in COSTCOMP different cost factors are given for various welding methods.

2.2. Fabrication time to even plates

Using a catalogue of a company, one can establish the time (T_4 [hour]) in the function of plate thickness (t [mm]) and area of the plate (A_p [m^2]).

The time function can be the following form:

$$T_4 = \delta_{de}\left(a_e + b_e t^3 + \frac{1}{a_e t^4}\right) A_p \tag{7}$$

where $a_e = 5.1*10^{-3}$, $b_e = 2.3*10^{-6}$, δ_{de} is a difficulty factor, δ_{de}=1,2 or 3 depends on the sizes and positions of the plates.

2.3. Surface preparation time

The surface preparation means the surface cleaning, painting costs, ground coat, top coat, sand-spraying, etc.

The surface cleaning time can be in the function of the surface area (A_s [m^2]) as follows:

$$T_5 = \delta_{ds} a_{sp} A_s \tag{8}$$

where $a_{sp} = 8.33*10^{-3}$ [hour/m^2], δ_{ds} is a difficulty factor depends on the sizes and positions of the plates.

2.4. Painting time

The painting means making the ground coat and the top coat.

The painting time can be in the function of the surface area (A_s [m^2]) as follows:

$$T_6 = \delta_{dp}(a_{gc} + a_{tc}) A_s \tag{9}$$

where $a_{gc} = 8.33*10^{-3}$ [hour/m^2] , $a_{tc} = 1.15*10^{-2}$ [hour/m^2], δ_{dp} is a difficulty factor, δ_{dp}=1,2 or 3 means horizontal, vertical or overhead painting.

2.5. Cutting and edge grinding times

The cutting and edge grinding can be made by hand grinding, hand flame cutting and machine flame cutting.

The cutting time can be in the function of the thickness and lengths (t [mm], L_e [m]) as follows:

$$T_7 = \delta_{dc}(a_{fc} + b_{fc} t^2) L_e \tag{10}$$

where

for hand grinding $a_{fc} = 4.12*10^{-2}$ [hour/m],
$b_{fc} = 6.82*10^{-3}$ [hour/m/mm^2],

for flame cutting $a_{fc} = 5.033*10^{-2}$ [hour/m],
$b_{fc} = 2.47*10^{-4}$ [hour/m/mm^2],

for machine flame cutting $a_{fc} = 3.45*10^{-2}$ [hour/m],
$b_{fc} = 2.28*10^{-4}$ [hour/m/mm^2],

δ_{dc} is a difficulty factor, δ_{dc}=1,2 or 3.

2.6. Total cost

The total cost contains all of the previous ones using time components as follows:

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m}(T_1 + T_2 + T_3 + T_4 + T_5 + T_6 + T_7) \tag{11}$$

One can establish other fabrication components, but the main problem is how to formulate the equation concerning to the time. The difficulty factor δ represents that the welding, or painting is above head, or vertical, or horizontal and also some uncertainty in costs.

2.7. Numerical examples

In order to show the effect of various welding methods on the optimal sizes and cost of welded structures, two illustrative numerical examples are worked out and the structural versions optimized for various welding methods are compared to each other.

2.8. Welded box beam (Fig. 6)

To simplify the calculations the transverse diaphragms are neglected. The box girder is subjected to a fluctuating load, so the maximal bending moment pulsates between 0 and M_{max} value, number of cycles is $N = 2*10^6$.

Two structural versions are considered as follows:, 1) the box beam is welded by 4 fillet welds (Fig.6a.),

2) the webs are welded to the flanges by 1/2 V butt welds (Fig.6b.). All welds are longitudinal and welded in downhand position. For both cases SMAW, GMAW-C and SAW methods are taken into account.

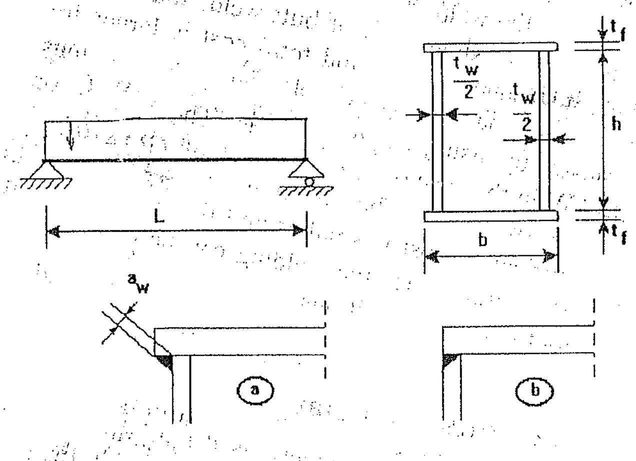

Fig. 6. Welded box beam a) with fillet welds, b) with 1/2 V butt welds

The total cost to be minimized is, according to Eqs. (2,3,4,5)

$$\frac{K}{k_m} = \rho LA + \frac{k_f}{k_m}(\delta\sqrt{\kappa\rho LA} + 1.3C_2a_w^n L_w) \quad (12)$$

where

$A = ht_w + 2bt_f$

$\delta = 3$, $\kappa = 4$, $L = 20*10^3$ mm, $L_w = 4L$, $\rho = 7.85*10^{-6}$ kg/mm^3, $C_2a_w^n$ are calculated according to Table 1-2.

To produce internationally useable solutions, the following ranges of k_m and k_f are considered. For steel Fe 360 k_m = 0.5 - 1.2 \$/kg, for fabrication including overheads k_f= 15 - 45 \$/manhour = 0.25 - 0.75 \$/min. Thus, the ratio k_f/k_m may vary in the range of 0 - 1.5 kg/min. The value k_f/k_m = 0 corresponds to the minimum weight design.

Design constraints are formulated according to *Eurocode 3* (1992).

Fatigue stress constraint

$$\Delta\sigma = \frac{\Delta M}{W_x} \le \frac{\Delta\sigma_C}{\gamma_f}, \qquad \Delta M = \frac{M_{max}}{2} \quad (13)$$

$\Delta M = 15*10^8$ Nmm.

The safety factor against fatigue for accessible joints, non fail-safe structure is γ_f=1.25.

The fatigue stress range $\Delta\sigma_C$ for $N = 2*10^6$ has to be chosen for the corresponding detail category. For longitudinal fillet or butt welds containing stop/start positions (SMAW, GMAW) $\Delta\sigma_C$ = 100 MPa, for automatic butt welds made from one side only, with backing bar, but without stop/start positions (SAW) $\Delta\sigma_C$ = 112 MPa. The moment of inertia and the section modulus are given by

$$I_x = \frac{h^3 t_w}{12} + 2bt_f\left(\frac{h+t_f}{2}\right)^2; W_x = \frac{I_x}{(h+t_f)/2} \quad (14)$$

Local buckling constraints for plate elements using the limiting plate slenderness concept are as follows.

For webs

$$\frac{t_w}{2} \ge \beta_w h; \beta_w = \frac{1}{124\varepsilon} \quad (15)$$

for compressed flange

$$t_f \geq \delta_f b; \delta_f = \frac{1}{42\varepsilon} \quad (16)$$

To avoid too thick flange plates an additional restriction is considered:

$$t_f \leq 1.2\delta_f b$$

Since for buckling the maximal normal stress 2 $\Delta\sigma$ has to be considered,

$$\varepsilon = \sqrt{\frac{235}{2\Delta\sigma / \gamma_f}} \quad (17)$$

Table 6. Optimal versions of the box beam welded with fillet welds by various welding methods. Rounded values in mm

Welding method	k_f/k_m	h	$t_w/2$	b	t_f	A (mm^2)	K/k_m (kg)
	0.0	1195	9	690	15	42210	6626
SMAW	0.5	1185	8	750	17	44460	8063
	1.0	1125	8	765	18	45540	9321
	1.5	1075	8	800	18	46000	10483
	0.0	1195	9	690	15	42210	6626
GMAW-C	0.5	1230	9	750	16	46140	7897
	1.0	1195	8	755	17	44790	8242
	1.5	1175	8	750	17	44300	8766
	0.0	1195	9	690	15	42210	6626
SAW	0.5	1170	9	700	16	43460	7349
	1.0	1145	9	685	17	43900	7947
	1.5	1130	8	690	17	41540	7991

Table 7. Optimal versions of the box beam welded with 1/2V butt welds by various welding methods. Rounded values in mm

Welding method	k_f/k_m	h	$t_w/2$	b	t_f	A (mm^2)	K/k_m (kg)
	0.0	1265	9	730	15	44670	7013
SMAW	0.5	1010	8	825	19	47510	9715
	1.0	880	7	900	21	50120	11459
	1.5	810	6	960	22	51960	12340
	0.0	1265	9	730	15	44670	7013
GMAW-C	0.5	1120	8	805	17	45290	8219
	1.0	1040	7	810	19	45340	8934
	1.5	965	7	850	20	47510	10201
	0.0	1195	9	690	15	42210	6627
SAW	0.5	1095	9	700	17	43510	7841
	1.0	1025	8	750	18	43400	8514
	1.5	970	7	780	19	43220	8910

The ranges of unknowns are taken as follows (in mm): h = 500 - 1500, $t_w/2$= 5 - 15, b= 300 - 1500, t_f= 5 - 25.

In the optimization procedure the unknown structural sizes h, $t_w/2$, b and t_f are determined which minimize the cost K and fulfil the design constraints.

The optimization procedure is carried out by using the software for the *Feasible Sequential Quadratic Programming* (FSQP) method developed by *Zhou and Tits* (1992) and for the *Rosenbrock's Hillclimb method.* Rounded values are computed by a complementary special program.

The results of the optimization are given in Tables 6-7.

It can be seen that the web thickness should be decreased when the fabrication cost increases, to decrease the weld size. If the web sizes decrease the flange sizes should be increased. This tendency is much stronger in the case of butt welds than that of fillet welds. The weight and total cost is larger for butt welds than for fillet welds. The cost savings achieved by using SAW instead of GMAW-C or SMAW in the case of k_f/k_m = 1.5 is about 11% and 26%, respectively. The advantage of SAW is that the fabrication cost is smaller and the fatigue stress range is larger since the welding can be carried out without stop/start positions.

2.9. Stiffened plate (Fig.7)

Stiffened panels are widely used in bridge and ship structures, so it is of interest to study the minimum cost design of such structural elements. On the other hand, it has been shown Farkas, Jármai (1993) that the fabrication cost of a welded stiffened plate represents a significant part of the total cost.

The design rules of *API* (1987) are used here for the formulation of the global buckling constraint for uniaxially compressed plate longitudinally stiffened by equally spaced uniform flat stiffeners of equal cross sections (Fig.7.). The cost function is defined according to Eqs (11) in which $A = b_0 t_f + \varphi h_s t_s$; $\delta = 3$; $\kappa = \varphi + 1$; $L_w = 2L\varphi$; φ is the number of stiffeners.

The flat stiffeners are welded by double fillet welds, the size of welds is taken as $a_w = 0.5t_s$. The welding costs are calculated for SMAW, GMAW-C and SAW according to Table 8.

In the optimization procedure the given data are as follows. The modulus of elasticity for steel is E =

$2.1*10^5$ MPa, the material density is $\rho = 7.85*10^{-6}$ kg/mm^3, the Poisson's ratio is $\nu = 0.3$, the yield stress is $f_y = 235$ MPa, the plate width is $b_0 = 4200$ mm, the length is $L = 4000$ mm. The axial compressive force is

$$N = f_y b_0 t_{fmax} = 235*4200*20 = 1.974*10^7 \text{ [N]}$$

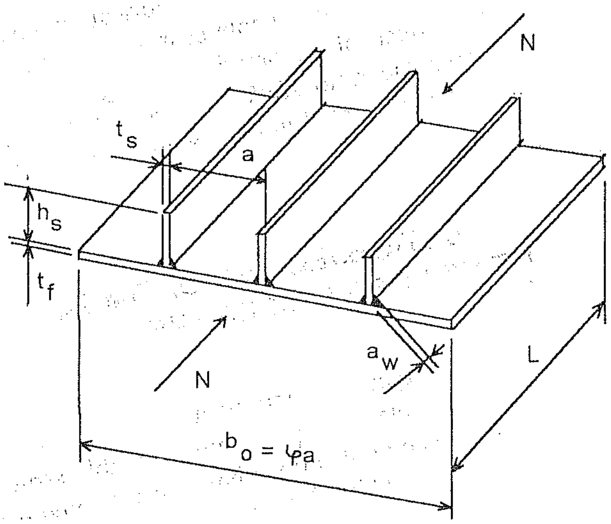

Fig. 7. Uniaxially compressed longitudinally stiffened plate

The variables to be optimized are as follows (Fig.7): the thickness of the base plate t_f, the sizes of stiffeners h_s and t_s and the number of stiffeners $\varphi = b_0/a$.

The overall buckling constraint is given by

$$N \le \chi f_y A \qquad (18)$$

where the buckling factor χ is given in function of the reduced slenderness $\bar{\lambda}$

$$\chi = 1 \quad \text{for} \quad \bar{\lambda} \le 0.5 \qquad (19a)$$

$$\chi = 1.5 - \bar{\lambda} \quad \text{for} \quad 0.5 \le \bar{\lambda} \le 1 \qquad (19b)$$

$$\chi = 0.5/\bar{\lambda} \quad \text{for} \quad \bar{\lambda} \ge 1 \qquad (19c)$$

where

$$\bar{\lambda} = \frac{b_0}{t_f}\sqrt{\frac{12(1-\nu^2)f_y}{E\pi^2 k}} \qquad (20)$$

$$k = min\,(k_R,\ k_F); \qquad k_R = 4\varphi^2 \qquad (21a,b)$$

$$k_F = \frac{(1+\alpha^2)^2 + \varphi\gamma}{\alpha^2(1+\varphi\delta_p)} \quad \text{when} \quad \alpha = \frac{L}{b_0} \le \sqrt[4]{1+\varphi\gamma} \qquad (21c)$$

$$k_F = \frac{2(1+\sqrt{1+\varphi\gamma})}{1+\varphi\gamma} \quad \text{when} \quad \alpha \ge \sqrt[4]{1+\varphi\gamma} \qquad (21d)$$

$$\delta_p = \frac{h_s t_s}{b_0 t_f}; \quad \gamma = \frac{EI_s}{b_0 D}; \quad I_s = \frac{h_s^3 t_s}{3};$$

$$D = \frac{Et_f^3}{12(1-\nu^2)} \qquad (21e)$$

so

$$\gamma = 4(1-\nu^2)\frac{h_s^3 t_s}{b_0 t_f^3} = 3.64\frac{h_s^3 t_s}{b_0 t_f^3} \qquad (21f)$$

I_s is the moment of inertia of one stiffener about an axis parallel to the plate surface at the base of the stiffener, D is the flexural stiffness of the base plate.

The constraint on local buckling of a flat stiffener is defined by means of the limiting slenderness ratio according to *Eurocode 3*.

$$\frac{h_s}{t_s} \le \frac{1}{\beta_s} = 14\sqrt{\frac{235}{f_y}} \qquad (22)$$

The computational results are summarized in Table 8.

Table 8. Optimal rounded sizes of a uniaxially compressed longitudinally stiffened plate, double fillet welds carried out by different welding methods, dimensions in mm

Welding method	k_f/k_m	t_f	h_s	t_s	φ	A (mm^2)	K/k_m (kg)
	0.00	10	200	15	15	87000	2732
	0.10	13	210	17	11	91560	3516
	0.18	15	220	16	9	94680	3929
SMAW	0.20	16	220	16	8	95360	3945
	0.50	19	230	17	6	103260	5272
	1.00	19	230	17	6	103260	7301
	1.50	19	230	17	6	103260	9330
	0.0	10	200	15	15	87000	2732
	0.3	15	215	16	9	93960	3716
GMAW -C	0.5	16	220	16	8	95360	4146
	1.0	19	230	17	6	103260	5227
	1.5	19	230	17	6	103260	6220
	0.0	10	200	15	15	87000	2732
SAW	0.5	15	220	16	9	94680	3944
	1.0	19	230	17	6	103260	4767
	1.5	19	230	17	6	103260	5530

The ranges of unknowns are taken as follows (in mm): $t_f = 6 - 20$, $h_s = 84 - 280$, $t_s = 6 - 25$, $\varphi = 4 - 15$.

It can be seen that the minimum weight design ($k_f = 0$) results in much more stiffeners than the minimum cost design. The optimal plate dimensions depend on cost factors k_f/k_m and C_2, so the results illustrate the effect of the welding technology on the structure and costs. It should be noted that, in the case of SMAW, the φ_{opt} values are very sensitive to k_f/k_m, so in Table 8 more k_f/k_m-values are treated. For $k_f/k_m = 1.5$ the cost savings achieved by using SAW instead of SMAW or GMAW-C are 100 (9330 - 5530) / 9330 = 41% and 100 (6220 - 5530) / 6220 = 11%. In the case of SMAW and $k_f/k_m = 1.5$ the material cost component is $\rho LA = 103260*7.85*10^{-6}*4*10^3 = 3242$ kg, so the fabrication cost represents 100(9330 - 3242)/9330 = 65% of the whole cost, this significant part of costs affects the dimensions and the economy of stiffened plates.

Using these cost functions the optimal dimensions of a box beam and a stiffened plate are computed which minimize the total cost and fulfil the design constraints. The comparison of optimal solutions shows that significant cost savings may be achieved by using SAW instead of SMAW or GMAW-C. The savings is larger for stiffened plate since the ratio K_f/K is much larger for stiffened plate than that for box beam.

Numerical computations show that the optimal sizes of a box beam or a stiffened plate depend on the applied welding method and illustrate the necessity of cooperation between designers and fabricators. The automatic welding methods are advantageous not only for welding time reduction but also for higher fatigue design stress, corresponding to detailed category for welds worked out without stop/start positions.

Comparison of optimal solutions for minimum weight ($k_f/k_m = 0$) and minimum cost shows that the fabrication cost affects significantly the optimal sizes, therefore the consideration of the total cost function results in more economic structural versions. Comparison of results for fillet and 1/2 V butt welds shows, that box beams with fillet welds are more economic, than those with 1/2 V butt welds. The weight and cost savings achieved by automatic welding depend of the ratio K_f/K. For structures in which the fabrication cost is higher compared to the whole cost, e.g. in stiffened plates, the effect of automation is higher. For stiffened plates the ratio K_f/K is about 65%, for the box beams calculated in our example this ratio is about 18%.

3. MULTIOBJECTIVE OPTIMUM DESIGN OF WELDED BOX BEAMS

The multiobjective optimization gives designers aspects for selection of the most suitable structural version. Some applications have been treated e.g. in Refs. Koski (1984), Osyczka (1984). Our aim is to show the application of multiobjective optimization technique in an illustrative numerical example of a simple welded box beam.

It has been shown that the fabrication cost affects the optimal dimensions of welded structures. Therefore we use not only the mass, but also the cost as objective function, which contains the material and fabrication costs. The deflection of a beam is often limited to fulfil the serviceability requirements. E.g. in Eurocode 3 (1992), the beam deflection is limited to $L/200$ -$L/500$, where L is the span length. Therefore our aim is to find structural solutions which minimize the maximal deflection.

The design constraints on stresses and local buckling of plate elements are formulated according to Eurocode 3. Several single- and multiobjective optimization methods are used to show their suitability for the solution of the defined nonlinear programming problem.

3.1. The objective functions

The cost function is defined by

$$K = K_m + K_f = k_m \rho V + k_f \Sigma T_i$$

where K_m and K_f are the material and fabrication costs, respectively, k_m and k_f are the respective cost factors, r is the material density, V is the volume of the structure, T_i are the times corresponding to the fabrication parts.

The times can be calculated using Eqs. (2,3,4,5) for manual arc welding C_2= 0.8*10^{-3} min/mm$^{2.5}$ and C_3= 0.24*10^{-3} min/mm$^{2.5}$

for automatic CO_2 -welding C_2= 0.4* 10^{-3} min/mm$^{2.5}$and C_3= 0.12*10^{-3} min/mm$^{2.5}$

To give internationally acceptable results, wide ranges of values for k_m and k_f are considered, i.e. k_m = 0.5 - 1.2 \$/kg, k_f= 15 - 45 \$/manhour = 0.25 - 0.75 \$/min, so the ratio k_f/k_m is varies in the range of 0 - 1.5 kg/min. The case of k_f=0 corresponds to the minimum weight design. Prices are in US\$.

In order to stiffen the box beam against the torsional deformation of the cross-sectional shape, some transversal diaphragms should be used. As shown in Fig. 8., in our example we use 7 diaphragms, so k= 11. Note that the mass of these diaphragms is neglected. For the four longitudinal fillet welds we consider the constants C_2 = 0.4*10^{-3} and C_3 = 0.12*10^{-3} [min/mm$^{2.5}$] , for manual-arc-welded transversal fillet welds connecting the diaphragms to the box beam we use C_2 = 0.8*10^{-3} and C_3 = 0.24*10^{-3} [min/mm$^{2.5}$].

For the difficulty factor we take Δ = 2, so the final formula of the cost function as the first objective function is

$$f_1 = K/k_m(kg) = \rho AL + k_f/k_m \quad (23)$$

$$f_l = \left[2\sqrt{\rho AL}\sqrt{11} + 0.52*10^{-3}*4L\left(\frac{t_w}{4}\right)^{1.5}\right] + \left[1.04*10^{-3}*7*2(2h+b)\left(\frac{t_w}{4}\right)^{1.5}\right] \quad (24)$$

Disregarding the fabrication costs, i.e. taking k_f= 0, we obtain the mass function as the second objective function

$$f_2 = \rho AL \quad (25)$$

The third objective function to be minimized is the maximal deflection of the beam due to the uniformly distributed normal static load p_0 neglecting the self mass

$$f_3 = \frac{5p_0L^4}{384EI_x} \quad (26)$$

where E = 2.1*10^5 MPa is the modulus of elasticity for steels,

I_x is the moment of inertia

$$I_x = \frac{h^3t_w}{12} + \frac{2bt_f^3}{12} + 2bt_f\left(\frac{h+t_f}{2}\right)^2$$

(27)

3.2. The design constraints

The constraint on bending stress, according to Eurocode 3, can be expressed as

$$\sigma_{max} = \frac{\gamma_1 M_{max}}{W_x} \le \frac{f_y}{\gamma_{M0}} \quad (28)$$

where the safety factors are as follows
g = 1.5 and g_{m0} =1.1

The bending moment is

$$M_{max} = \frac{pL^2}{8} \quad (29)$$

Considering also the self mass

$$p = p_0 + \rho A g \quad (30)$$

where g = 9.81 m/s^2 is the gravitational acceleration.

Furthermore, f_y is the yield stress, for steel Fe 360 f_y = 235, for steel Fe 510, f_y = 355 MPa.

The section modulus is

$$W_x = \frac{I_x}{\frac{h}{2} + t_f} \quad (31)$$

Note that we consider the cross section of class 3 that means that the stress distribution is linear elastic and the yield stress is reached in extreme fibre without any local buckling of plate elements.

Local buckling constraint for compressed upper flange

$$t_f \ge \delta b\ ;\ 1/\delta = 42\,\varepsilon\ ;\ \varepsilon = \sqrt{\frac{235}{\sigma_{max}}} \quad (\sigma_{max} \text{ in MPa}) \quad (32)$$

and for bent webs

$$t_w/2 \ge \beta h\ ;\ 1/\beta = 124\,\varepsilon \quad (33)$$

The shear constraint can be expressed according to Eurocode 3 for $1/\beta$= 124

$$Q_{max} = \frac{\gamma_1 pL}{2} \le 0.627*0.5\,Q_b \quad (34)$$

where

$$Q_b = \frac{ht_w}{\gamma_{M1}}\frac{f_y}{\sqrt{3}}$$

With $\gamma_{m1} = 1.1$ Eq. (34) takes the form

$$\frac{\gamma_1 pL}{2} \leq 0.1645 h t_w f_y \qquad (35)$$

Since the deflection minimization leads to maximization of the beam dimensions, size constraints should be defined as follows

$$h \leq h_{max} \,;\, t_w \leq t_{wmax} \,;\, b \leq b_{max} \,;\, t_f \leq t_{fmax} \qquad (36)$$

3.3. The optimization procedure

In the optimization procedure the optimal values of variables h, t_w, b and t_f should be determined which minimize the objective functions and fulfil the design constraints.

Note that for the single-objective problem to minimize the mass f_2, the following approximate formulae can be derived Farkas (1984)

$$h = \sqrt[3]{0.75 W_0 / \beta} \;;\; t_w/2 = \beta h \;;$$

$$b = h\sqrt{\beta / \delta} \;;\; t_f = \delta b \qquad (37)$$

where $W_0 = \dfrac{\gamma_1 M_{max}}{f_y / \gamma_{M0}}$ is the required section modulus.

For the computer-aided optimum design a decision support system has been developed Jármai (1989a, 1989b) containing five single-objective and seven multiobjective optimization techniques. The single objective optimization methods are as follows: Himmelblau's method of Flexible Tolerances, Weisman's Direct Random Search method, Rosenbrock's Hillclimb method, Complex method of Box and the Davidon-Fletcher-Powell method.

The multiobjective optimization methods are as follows: min-max, weighting min-max, global criterion type 1 and 2, weighting global criterion, pure weighting; and normalized weighting method.

A multicriteria optimization problem can be formulated as follows :

Find x such that

$$f(x^*) = opt\, f(x), \qquad (38)$$

such that

$$g_j(x) \geq 0 \qquad j = 1,\ldots,m$$

$$h_i(x) = 0 \qquad i = 1,\ldots,q$$

where x is the vector of decision variables defined in n-dimensional Euclidean space and $f_k(x)$ is a vector function defined in r-dimensional Euclidean space. $g_j(x)$ and $h_i(x)$ are inequality and equality constraints.

The solutions of this problem are the Pareto optima. The definition of this optimum is based upon the intuitive conviction that the point $\mathbf{x}^*$ is chosen as the optimal, if no criterion can be improved without worsening at least one other criterion.

We have used the min-max, the weighting min-max, two types of global criterion, weighting global criterion, pure weighting and normalized weighting techniques. They are described in details in Osyczka (1984), Jármai (1989a).

3.4. Brief description of the methods

The min-max optimum compares relative deviations from the separately reached minima. The relative deviation can be calculated from

$$z_i'(x) = \frac{|f_i(x) - f^0_i|}{|f^0_i|} \quad \text{or} \quad z_i''(x) = \frac{|f_i(x) - f^0_i|}{|f_i(x)|} \qquad (39)$$

If we know the extremes of the objective functions which can be obtained by solving the optimization problems for each criterion separately, the desirable solution is the one which gives the smallest values of the increments of all the objective functions. The point x^* may be called the best compromise solution considering all the objective functions simultaneously and on equal terms of importance.

$$z_i(x) = max\,\{ z_i'(x), z_i''(x) \} \qquad i \in I \qquad (40)$$

$$\mu(x^*) = min\, max\,\{ z_i(x) \} \qquad x \in X \quad i \in I \qquad (41)$$

where X is the feasible region.

The weighting min-max method one gets combining the min-max approach with the weighting method, a desired representation of Pareto optimal solutions can be obtained

$$z_i(x) = max\,\{ w_i z_i'(x),\, w_i z_i''(x) \} \qquad i \in I \qquad (42)$$

The weighting coefficients w_i reflect exactly the priority of the criteria, the relative importance of it.

We can get a distributed subset of Pareto optimal solutions.

Global criterion method means that a function which describes a global criterion is a measure of closeness the solution to the ideal vector of f^0. The common form of this function is (type 1) :

$$f(x) = \sum_{i=1}^{r} ((f_i^0 - f_i(x)) / f_i^0)^P \qquad (43)$$

It is suggested to use P=2, but other values of P such as 1,3,4, etc. can be used. Naturally the solution obtained will differ greatly according to the value of P chosen.

It is recommended to use relative deviations (type 2):

$$L_P(f) = \left[\sum_{i=1}^{r} \left| \frac{f^0{}_i - f_i(x)}{f^0{}_i} \right|^P \right]^{1/P} \qquad 1 \le P \le \infty \qquad (44)$$

The weighting global criterion method is made, by introducing weighting parameters one could get a great number of Pareto optima. If we choose P=2, which means the Euclidean distance between Pareto optimum and ideal solution (Jármai 1989a). The coordinates of this distance are weighted by the parameters as follows:

$$L_P(f) = \left[\sum_{i=1}^{r} w_i \left| \frac{f^0{}_i - f_i(x)}{f^0{}_i} \right|^P \right]^{1/P} \qquad 1 \le P \le \infty \qquad (45)$$

The pure weighting method means to add all the objective functions together using different weighting coefficients for each. It means, that we transform our multicriteria optimization problem to a scalar one by creating one function of the form:

$$f(x) = \sum_{i=1}^{r} w_i f_i(x)$$

where $w_i \ge 0$ and $\sum_{i=1}^{r} w_i = 1$ (46)

If we change the weighting coefficients result of solving this model can vary significantly, and depends greatly from the nominal value of the different objective functions.

The normalized weighting method solves the problem of the pure weighting method e.g.at the pure weighting method, the weighting coefficients do not reflect proportionally the relative importance of the objective, because of the great difference on the nominal value of the objective functions. At the normalized weighting method w_i reflect closely the importance of objectives.

$f(x) = \sum_{i=1}^{r} w_i f_i(x) / f_i^0$ where $w_i \ge 0$ and

$$\sum_{i=1}^{r} w_i = 1 \qquad (47)$$

The condition $f_i^0 \neq 0$ is assumed.

3.5. The results of a numerical example

Data: p_o = 80 kN/m, L = 15 m, r = 7850 kg/m^3, h_{max} = 1800, b_{max} = 1000, t_{wmax} = 40, t_{fmax} = 40 mm.

Table 9 shows the results of the single-objective optimization using three different techniques. The differences between results are very small. All the techniques treat the variables as continuous ones and give unrounded optima. To give plate sizes available in the market, a secondary search is used for finding the discrete optima. The discrete steps for h and b are 50 mm, for thicknesses $t_w/2$ and t_f 1 mm.

In Table 10. the multiobjective - Pareto - optima are given, obtained using five different techniques, for steel Fe 360 and for the ratio k_f/k_m = 1.5. Fig. 9. shows the results in the coordinate-system f_1 - f_3, for steels Fe 360 and Fe 510. The notation f_1^{510} means the optimum of f_1 for steel Fe 510.

The Pareto-optima for various weighting coefficients of the weighting min-max technique can be seen between the limiting points of the single-objective optima. Note that the points c/ are the same also for min-max technique. It can be seen that the single-optimum of the deflection f_3 does not depend on the steel type, i.e. $f_3^{360} = f_3^{510}$.

It can be seen from the Table 11. that cost savings of 24% may be achieved using Fe 510 instead of Fe 360, but the deflection will be nearly doubled.

Table 12. shows the results of the single-objective optimization for Fe 360 and k_f/k_m = 1.5 for the three objective functions.

Fig. 10. and 11. show the effect of the relative importance of an objective function on the value of the other objective function.

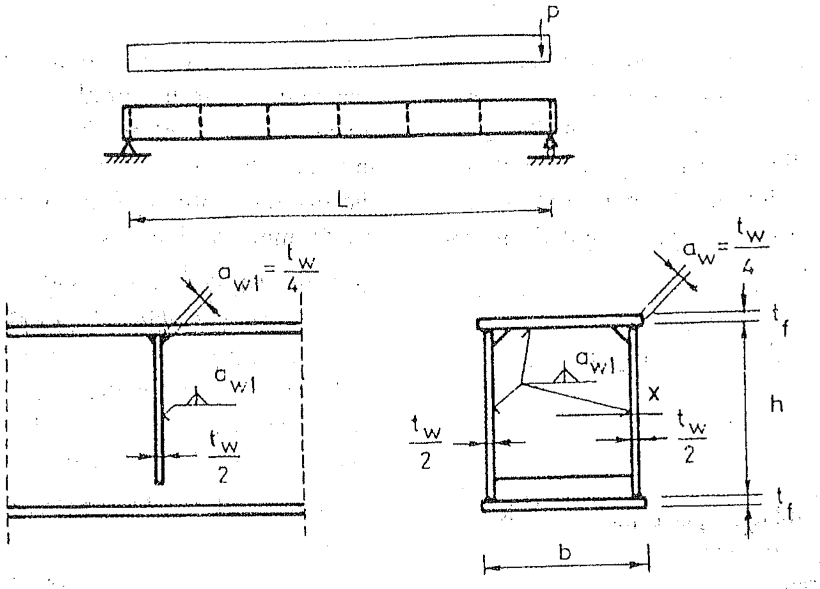

Fig. 8. Welded box beam with transverse diaphragms

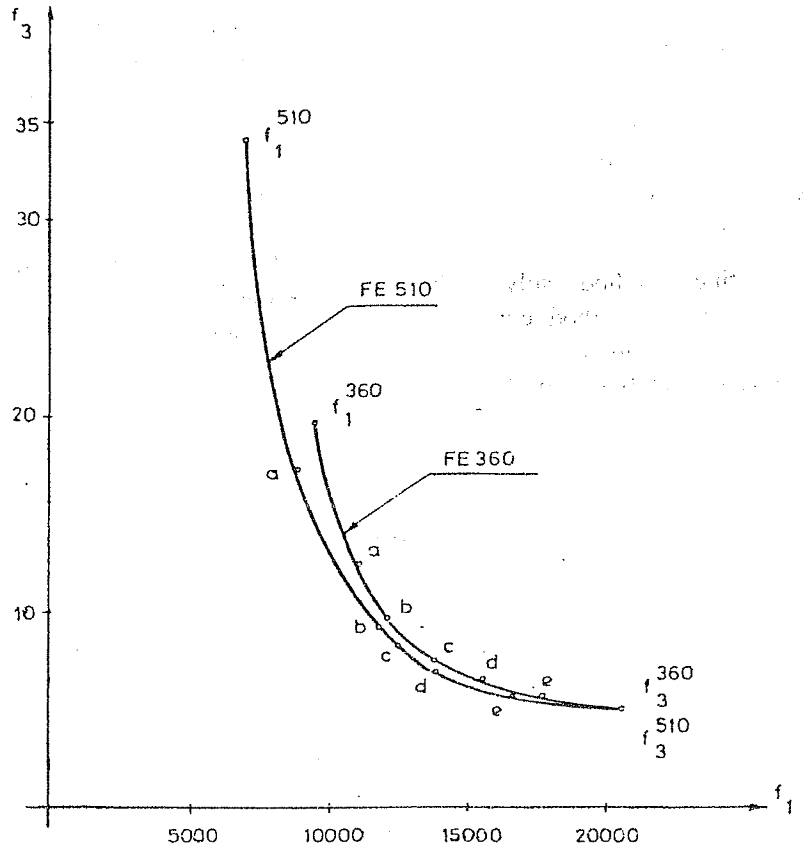

Fig. 9. Optima in a coordinate-system f_1-f_3 for various weighting coefficients, for steels Fe 360 and Fe 510, according to the weighting min-max technique. The points relate to the following weighting coefficients: a) w_1=0.90, w_2=0.10, b) w_1=0.75, w_2=0.25; c) 0.50/0.50, d) 0.25/0.75 and e) 0.10/0.90

The investigated numerical example illustrates the possibilities given for designers to select the most suitable structural version considering the cost, mass and maximal deflection of a structure.

It can be seen from Table 12. that the fabrication cost is about 26% of the total cost and therefore does not affect significantly the optima. This effect is much more significant in the case of a stiffened plate as it has been show in another study.

The deflection minimization leads to maximal prescribed sizes and to significant increase of cost and mass. The use of steel Fe 510 instead of Fe 360 results in 24% cost savings without deflection minimization and no savings considering the deflection minimization.

The multiobjective optimization gives structural versions for selected weighting coefficients according to Table 10. and Fig. 9.

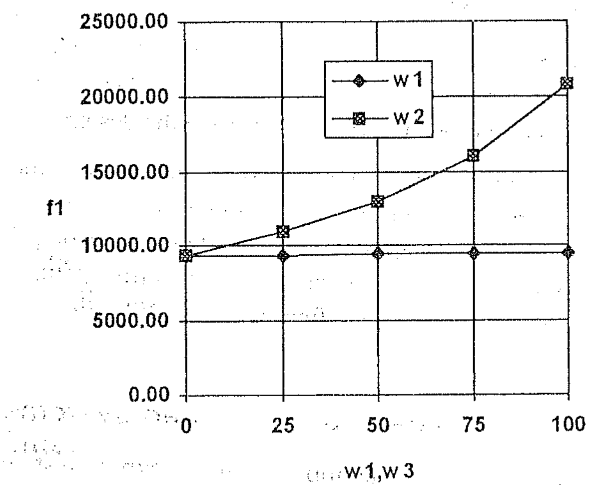

Fig. 10. Effect of weighting coefficients w_2 and w_3 on f_1

Table 9

Characteristics of beams optimized using different single-objective techniques

Technique		h (mm)	t_w	b	t_f (mm)	f_1 (kg)	f_3 (mm)
Flexible tolerance	f_{1min}	1450	22	700	19	9332	19.7
	f_{3min}	1800	32	1000	40	20801	5.1
Direct random search	f_{1min}	1400	22	650	22	9402	20.5
	f_{3min}	1800	32	1000	40	20801	5.1
Hillclimb	f_{1min}	1300	20	550	32	9343	21.9
	f_{3min}	1800	32	1000	40	20801	5.1

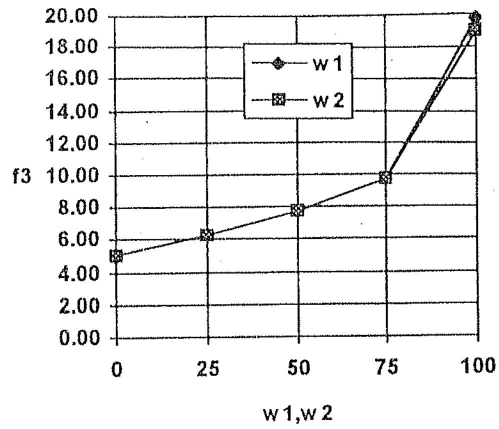

Fig. 11. Effect of w_1 and w_2 on f_3

Table 10.

Characteristics of beams optimized using different multiobjective optimization methods and various weighting coefficients

Technique		h mm	t_w	b	t_f mm	f_1 (kg)	f_3 (mm)
min-max		1800	20	750	39	13762	7.3
global 1,	P=3	1800	20	750	40	13947	7.2
global 2,	P=5	1800	20	900	33	13910	7.2
weighting min-max	w_1/w_3 0.9/0.1	1750	24	700	18	10834	12.2
	0.75/0.25	1800	22	950	20	11974	9.5
	0.5/0.5	1800	20	750	39	13762	7.3
	0.25/0.75	1800	18	1000	38	15294	6.1
	0.1/0.9	1800	24	1000	40	17869	5.5
weighting global	0.9/0.1	1800	22	950	20	11974	9.5
	0.75/0.25	1800	20	900	28	12799	8.2
	0.5/0.5	1800	20	950	35	14329	7.0
	0.25/0.75	1800	18	950	40	15284	6.1
	0.10/0.9	1800	18	1000	40	15786	5.9
normalized weighting	0.9/0.1	1800	26	500	13	10136	14.0
	0.75/0.25	1800	22	950	20	11974	9.5
	0.5/0.5	1800	18	950	40	15284	6.1
	0.25/0.75	1800	22	950	40	16658	5.9
	0.1/0.9	1800	32	1000	40	20801	5.1

Table 11.

Characteristics of optimized beams made of steel Fe 360 and Fe 510

Tech-nique		h (mm)	t_w	b	t_f (mm)	f_1 (kg)	f_3 (mm)
Fe 360							
Single-objective	f_{1min}	450	22	700	19	9332	19.7
optimiza-tion	f_{3min}	1800	32	1000	40	20801	5.1
min-max method		1550	30	750	25	16343	8.8
Fe 510							
Single-objective	f_{1min}	1300	20	500	17	7051	34.2
optimiza-tion	f_{3min}	1800	32	1000	40	20301	5.1
min-max method		1500	24	750	40	14253	10.2

Table 12.

Characteristics of beams optimized using single-objective optimization technique

Objec-tive func-tion	h (mm)	t_w	b	t_f (mm)	f_1 (kg)	f_2 (kg)	f_3 (mm)
$f1$	1450	22	700	19	9332	6888	19.7
$f2$	1500	24	700	16	9577	6876	19.0
$f3$	1800	32	1000	40	2080	16202	5.1

4. OPTIMIZATION OF MAIN GIRDERS OF OVERHEAD TRAVELLING CRANES BY EXPERT SYSTEMS

The emerging fields of AI and knowledge engineering offer means to carry out qualitative reasoning on computers. Advanced programs that can solve a variety of new problems based on stored knowledge without being reprogrammed, are called knowledge-based systems. If there level of competence approaches that of human experts, they become expert systems, which is the popular name for all knowledge systems, even if they do not deserve the name.

AI techniques provide powerful symbolic computation and reasoning facilities that accommodate intuitive knowledge used by experienced designer. AI techniques, knowledge engineering in particular, can be used in conjunction with numerical programs to serve as an interface between the alternatives and constraints and the designer. AI should be used in the following context (Adeli 1988).

- to track the available design alternatives and relevant constraints and to infer candidate modifications in order to improve the design,

- to observe the relationship - intuitive or numerical - between specifications and decision variables, and give advice on how to formulate the problem for optimization, in particular, to identify the limiting constraints and specifications.

4.1. Capabilities of expert systems

Depending on the application, an expert system can perform ten type of projects as follows: *interpretation, prediction, diagnosis, design, planing, monitoring, debugging, repair, instruction, control.* We've used the expert systems for design.

4.2. Components of an expert system

The three basic components of an expert system are

- the knowledge base,

- the inference engine,

- the user interface.

There are three main streams at expert systems

- rule-based expert systems can be backward or forward chaining,

- object-oriented systems,

- hybrid systems, which combine object-oriented techniques with rule-based ones, Harmon, Sawyer (1990), Garrett (1990), Gero (1990).

There were some attends to connect the expert systems and structural optimization. One of them is an expert system for finding the optimum geometry of steel bridges Balasumbramadan (1990).

The connection of single- and multiobjective optimization made it possible at the structural optimization to form a decision support system. At the multiobjective optimization there are several so called weighting coefficients for the designer to give the relative importance of the objective functions

Jármai et al (1994). The decision support systems (DSS) and the expert systems (ES) are close together, but it is necessary to build an inference engine. The key concept in our approach is to give the user control of important design decisions.

Therefore, our approach in applying AI to engineering design is to use AI techniques for keeping track of all the design alternatives and constraints, for evaluating the performance of the proposed design by means of a numerical model, and for helping to formulate the optimization problem. The human designer evaluates the information and advices given by the computer, assesses whether significant constraints or alternatives have been overlooked, decides on alternatives, and makes relevant design decisions.

4.3. Overview on Personal Consultant Easy

Personal Consultant Easy (EASY) is an EMYCIN-like program developed by Texas Instruments to run on PC-s. Fact are represented as object-attribute-value triplets with accompanying confidence factors. Production rules represent heuristic knowledge. Personal Consultant can build systems of up to about 400 rules. A rule tests the value of an O-A-V fact and concludes about other facts. The inference engine is a simple back-chainer.

Control is governed primarily by the order of clauses in the rules. Uncertain information is marked by confidence factors ranging from 0 to 100. Personal Consultant accepts unknown as an answer to its questions and continues to reason with available information. There are explanation facilities in the program as well as trace functions for knowledge base debugging. Personal Consultant uses questions to prompt the designer to enter the initial information into a knowledge base. The tool provides several programming aids for debugging.

Personal Consultant is implemented in IQLISP. Sources of data can be other language programs or procedures such as FORTRAN, C, C++, data bases such as DBASE, LOTUS. The program has some graphics functions as well (DR HALO). The tool uses an Abbreviated Rule Language, ARL, to write the rules.

4.4. Overview the Level 5 Object

LEVEL 5 OBJECT (1990), (LO5) is an object-oriented expert system development and delivery environment. It provides an interactive, windows-based user interface integrated with Production Rule Language (PRL), the development language used to create L5O knowledge bases. The PRL Syntax Section provides syntax diagrams to follow logically when writing a knowledge base. System classes are automatically built by L5O when a new knowledge base is created, thereby providing built-in logic and object tools. The developer can use system classes in their default states or customize them. In this way, the developer can control devices, files, database interactions and the inferencing and windowing environments.

The most remarkable tools of LO5 are:

- object oriented programming (OOP),
- relational database handling (RDB),
- computer aided software engineering (CASE), and
- graphical development system.

The most remarkable tools of LO5 for IBM compatible PCs are:

- Microsoft Windows,
- programming with an object-oriented language (Borland C++),
- direct connection with dBase,
- direct connection with the fourth generation FOCUS data handling system,
- EDA/SQL interface to relational and non-relational databases,
- Rdb/SQL interface to VAX RDB/VMS databases, and
- own worksheet handling system (similar to LOTUS 123).

Using LO5 there are two ways of developing programmes: they can be generated either by word processors or in the developing environment. Taking these capabilities into account, LEVEL5 OBJECT was found suitable for development expert systems for structural engineering. There are a great number of expert shells available such as ART (Automated Reasoning Tool, Inference Corporation), KEE (Intellicorp), Intelligence Compiler (Intelligence Ware Inc.), Symbologic Adept (Symbologic Corporation), GURU (Micro Data Base Systems),

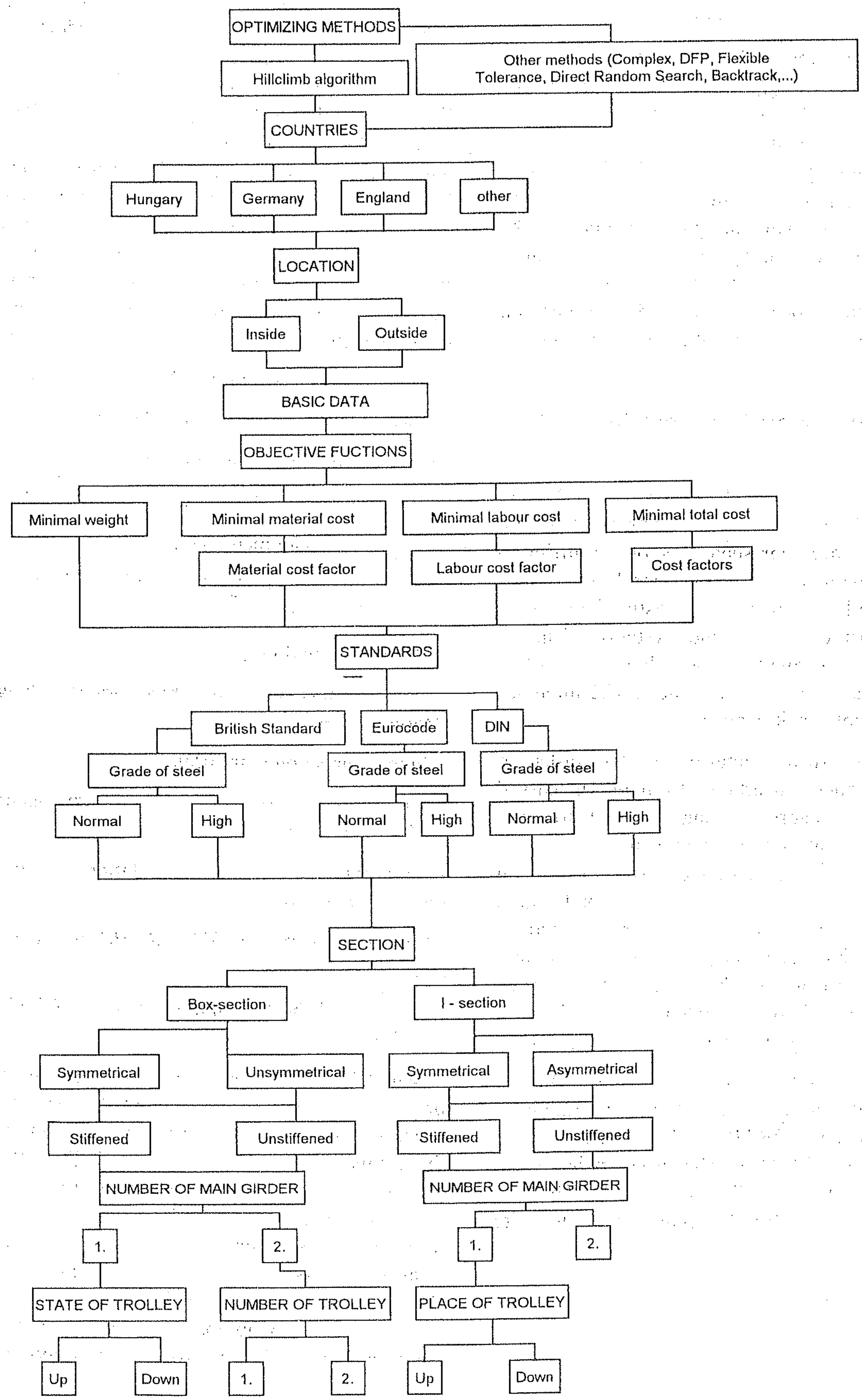

Fig. 12. The logical structure of the expert system for crane girder design

etc. They are available on APOLLO or SUN workstations or on PC-s.

We've developed the optimization package on PC and we've found the previously described two softwares to be efficient expert shells, so we've made our development using these tools.

4.5. Application of an expert system for the optimum design of the main girders of overhead travelling cranes

The aim was to develop an expert system, which is able to find the optimum sizes of the welded box girder of the crane due to different geometry, loading, steel grades and design codes. The different variants can be seen in Fig. 12.

The total number of variants is about 60000 and it can be increased if we take into account other aspects and constraints in a modular way.

The decision support system, which was connected to the expert one, constraints 5 various single-objective and 7 various multiobjective optimization techniques. These techniques are able to solve nonlinear optimization problems with practical nonlinear inequality constraints. It could contain finite element procedures to compute the mechanical behaviour of the structures. The DSS system is described in (Jármai 1989a, 1989b).

4.6. Objective functions

- material cost of the girder, $C_m = k_m * \rho * V$ [kg], where ρ is the material density, V is the volume of the girder, k_m is the specific material cost.

- labour cost contains welding cost and surface preparation cost $C_l = C_w + C_s$,

- welding cost, $C_w = k_w*(a^2_w/\sqrt{2})*L_w* \rho *k_c$ [$], where a_w is the effective size of weldment, L_w is the length of weldment, k_c is the difficulty factor of welding, which depends on the position of welding.

- surface preparation and painting costs, $C_s = k_s*(2*b*L+2*h*L)$ [$], where b and h are width and height of the girder, k_s is the specific cost of manufacturing.

total cost contains material and labour costs $C_t = C_m + C_l$

4.7. Design constraints

- constraint on the static stress at midspan due to biaxial bending according to BS 2573 (1983) and 5400 (1983) is described by

$$M_x/W_y + M_y/W_y \leq \alpha_d *P_s \quad (48)$$

where M_x, M_y are the bending moments, W_x, W_y are section moduli,

P_s is the permissible static stress, α_d is the duty factor.

- constraint on fatigue stress is as follows

$$M_{xf}/W_x + M_y/W_y \leq P_{ft} \quad (49)$$

where M_{xf} contains the live load multiplied by the impact, factor and the spectrum factor. P_{ft} is the fatigue stress.

- local flange buckling constraint is

$$\sigma_{1f}/(P_s*K_{1f}) + \{(\sigma_{bf}/(P_s*K_{bf})\}^2 \leq 1, \quad (50)$$

where $\sigma_{1f} = M_x/W_x$; $\sigma_{bf} = M_y/W_y$, the K factors depend on the slenderness of the plate

$\lambda_f = (b/t_f)*\sqrt{R_{yf}/355}$, where R_{yf} is the yield stress of the flange plate

- local web buckling constraint is

$$\sqrt{\{(0.8{*}\sigma\sigma_{1f} + \sigma_{bw})/(P_s{*}K_{1w})\}^2 + \{(\sigma_{cw}/(P_s{*}K_{2w})\}^2 + \{(0.2{*}\sigma_{1f}/(P_s/K_{bw})\}^2 + 3{*}(\tau_q/P_s/K_{qw})^2} \leq 1 \quad (51)$$

where $\sigma_{bf} = \sigma_{bw}$; $\sigma_{cw} = F/(t_{1w}*a_w)$; $a_w = 50 + 2(h_r+t_f\text{-}5)$

the K factors depend on the slenderness of the plate

$\lambda_e = (h_w/t_{w1})*\sqrt{R_{yw}/355}$, where R_{yw} is the yield stress of the web plate.

h_r is the height of the rail.

overhead travelling crane

- local web buckling constraint on the secondary web is similar to the main web one, but we have to use t_{w2} instead of t_{w1} and there is no local compression, so $\sigma_{cw} = 0$.

- deflection constraint due to wheel load can be expressed as

$w_{max} \leq L/(800\text{-}1000)$, where L is the span length.

4.8. Example

Main data of an example solved by Personal Consultant

Hook load is H = 240 kN, length is L = 25 m, mass of trolley is G_t= 30kN, distance between the trolley axes is k = 2.5 m, height of rail is h_r = 50 mm, mass of the rail is p_r = 80 kg/m, the Young module is E = 2.06 GPa, class of the crane is A7, steel grade is Fe 430, stiffeners are 120*80*8 mm angle profiles.

The program is made in MS FORTRAN 5.0 on IBM PC/AT 486 type computer. In the expert system one part of the rules are concerning to the selection of the crane (see Fig. 12.). The second part is concerning to the selection of optimization techniques.

The weighting factors at the multiobjective optimization system and the uncertainty parameters at the expert system for the various objective functions are the same. There ranging is fróm 0 to 100 percent. It means the relative importance of the objective function.

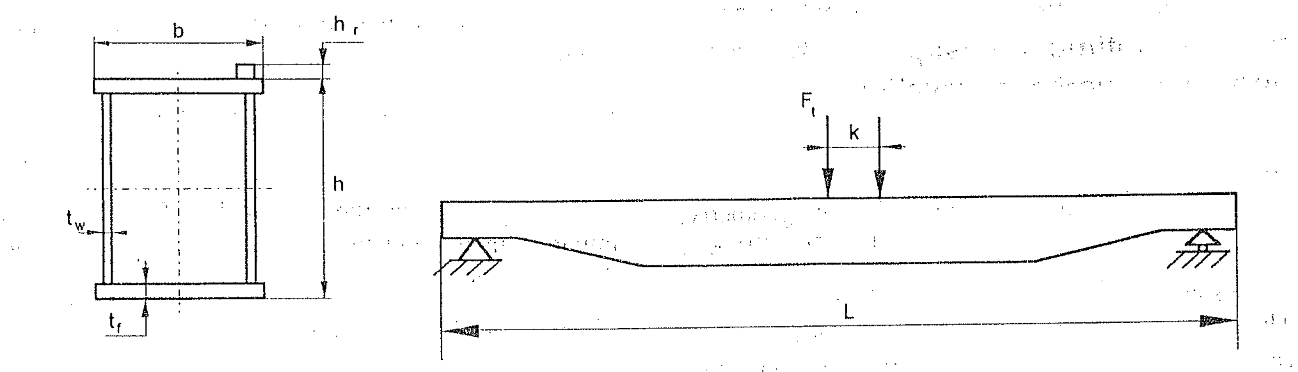

Fig. 13. Cross section of the welded main girder of

The third part of the rules are concerning to the results of the optimization, to choose the smallest objective function value, where the ratio of web height and flange width and the ratio of the two web thicknesses are acceptable. For the first ratio it is given to be near to the golden ratio, for the second ratio it has technological reasons.

$0.4 \leq b/h \leq 0.8$; $t_{w1}/t_{w2} \leq 1.5$

The result for a crane girder is determined with box girder section, asymmetrical section, stiffeners on the webs, two main girders, one trolley and the degree of interest of total cost = 0.4 , material cost = 0.3, labour cost = 0.3. Specific costs are: material cost k_m = 1.[\$/kg], welding cost k_w = 10. [\$/kg], surface preparation cost k_s = 100. [\$/m^2] .

web height is	h = 1260.	[mm],
main web thickness is	t_{w1} = 6.	[mm],
secondary web thickness is	t_{w2} = 5.	[mm],
width of the flange is	b = 700.	[mm],
thickness of the flange is	t_f = 18.	[mm],
total cost of the structure is	C_t = 16677.04	[\$]

The discrete value ranges of the variables are as follows: for h and b the step sizes were 20 [mm], for the thicknesses step sizes were 1 [mm]. Further development can be the installation of the new Eurocodes in the analysis to build the system in Borland C++, to use the Object Oriented Programming (OOP).

The main differences using the Personal Consultant and the LEVEL 5 OBJECT expert shells were, the at EASY all values for the computation should be given in advance, so the program goes on a given way bordering by the rules, but LO5 asks for the unknowns during the computation, it knows what to ask for, more easy to jump from one level to another on the rules' tree and the optimum computation part is build into the expert shell. It means, that the second application is much close the original aim of artificial intelligence.

5. MISCELLANEOUS

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