HOW TO CALCULATE THE WELDING AND CUTTING COST OF A STRUCTURE?

Károly Jármai[1] and József Farkas[2]

[1] Professor, University of Miskolc, H-3515 Miskolc, Egyetemváros, Hungary
[2] Emeritus Professor, University of Miskolc, H-3515 Miskolc, Egyetemváros, Hungary

ABSTRACT

The cost function includes the cost of material, assembly, welding as well as surface preparation, painting and cutting, edge grinding, forming the shell and is formulated according to the fabrication sequence. The paper describes the new cost calculations of the different technologies, considering some newer technologies like laser, plasma, waterjet, etc. These costs are the objective functions in structural optimization.

KEYWORDS: welding cost, cutting cost, fabrication cost calculation, structural optimization

1 INTRODUCTION

This paper describes the importance of cost calculations when we optimize a structure. These cost calculations are founded on material costs and those fabrication costs, which have direct effect on the sizes, dimensions or shape of the structure. The cost function includes the cost of material, assembly, welding as well as surface preparation, painting and cutting, edge grinding, forming the shell and is formulated according to the fabrication sequence. Other costs, like amortization, investment, transportation, maintenance are not considered here. Sometimes we can predict the cost of design and inspection, but usually they are proportional to the weight of the structure. Cost and production time data come from different companies from all over the world. When we compare the same design at different countries, we should consider the differences between labour costs. It has the most impact on the structure, if the technology is the same. This paper describes the new cost calculations of the different technologies, considering some newer technologies like laser, plasma, waterjet, etc. These costs are the objective functions in structural optimization.

When we consider the interaction of design and fabrication technology, we should not forget about the cost as the third important characteristic of the structure. These three together help us to find the best solution.

2 THE COST FUNCTION

The cost function of a real structure may include the cost of material, assembly, the different fabrication costs such as welding, surface preparation, painting and cutting, edge grinding, forming the geometry, etc. There are some researches, which have been done in this field like Klansek & Kravanja (2006a,b), Jalkanen (2007), Tímár et al. (2003), Farkas & Jármai (1997,2003,2008), Bader (2002). For composites the calculation is very different and there are some good information available on the internet (Catalog 2012, Cost studio 2012).

2.1 The cost of materials

$$K_M = k_M \rho V \, , \tag{1}$$

For steel the specific material cost can be k_M=1.0-1.3 \$/kg, for aluminium k_M= 3.0-3.5 \$/kg, for stainless steel k_M = 6.0-7.1 \$/kg, for glass fibre 20-30 \$/m^2 depending on the thickness.

K_M [kg] is the fabrication cost, k_M [\$/kg] is the corresponding material cost factor, V [mm^3] is the volume of the structure, ρ is the density of the material. For steel it is 7.85x10^{-6} kg/mm^3, for aluminium 2.7x10^{-6} kg/mm^3, for stainless steel 7.78x10^{-6} kg/mm^3, for glass fibre 2.5x10^{-6} kg/mm^3. If several different materials are used, then it is possible to use different material cost factors simultaneously in Eq. (1).

2.2 The fabrication cost in general

$$K_f = k_f \sum_i T_i \tag{2}$$

where K_f [\$] is the fabrication cost, k_f [\$/min] is the corresponding fabrication cost factor, T_i [min] are production times. It is assumed that the value of k_f is constant for a given manufacturer. If not, it is possible to apply different fabrication cost factors simultaneously in Eq. (2).

2.2.1 Fabrication times for welding

The main times related to welding are as follows: preparation, assembly, tacking, time of welding, changing the electrode, deslagging and chipping.

Calculation of the times of preparation, assembly and tacking

The times of preparation, assembly and tacking can be calculated with an approximation formula as follows

$$T_{w1} = C_1 \Theta_{dw} \sqrt{\kappa \rho V} \, , \tag{3}$$

where C_1 is a parameter depending on the welding technology (usually equal to 1), Θ_{dw} is a difficulty factor, κ is the number of structural elements to be assembled. The difficulty factor expresses the complexity of the structure. Difficulty factor values depend on the kind of structure (planar, spatial), the kind of members (flat, tubular). The range of values proposed is between 1-4 (Farkas & Jármai 1997).

Calculation of real welding time

Real welding time can be calculated on the following way

$$T_{w2} = \sum_i C_{2i} a_{wi}^2 L_{wi} , \tag{4}$$

where a_{wi} is weld size, L_{wi} is weld length, C_{2i} is constant for different welding technologies. C_2 contains not only the differences between welding technologies but the time differences between positional (vertical, overhead) and normal welding in downhand position as well. The equations for different welding technologies can be found in the Farkas, Jármai (2008).

Calculation of additional fabrication actions time

There are some additional fabrication actions to be considered such as changing the electrode, deslagging and chipping. The approximation of this time is as follows

$$T_{w3} = 0.3 \sum C_{2i} a_{wi}^2 L_{wi} . \tag{5}$$

Table 1 Welding times T_{w2} (min/mm) in the function of weld size a_w (mm) for longitudinal fillet welds, downhand position

Welding technology	a_w [mm]	$10^3 T_{w2} = 10^3 C_2 a_w^2$
SMAW	0-15	$0.7889 a_w^2$
SMAW HR	0-15	$0.5390 a_w^2$
GMAW-C	0-15	$0.3394 a_w^2$
GMAW-M	0-15	$0.3258 a_w^2$
FCAW	0-15	$0.2302 a_w^2$
FCAW-MC	0-15	$0.4520 a_w^2$
SSFCAW (ISW)	0-15	$0.2090 a_w^2$
SAW	0-15	$0.2349 a_w^2$

In is proportional to T_{w2}. It is the 30% of it. The two time elements are as follows:

$$T_{w2} + T_{w3} = 1.3 \sum C_{2i} a_{wi}^n L_{wi} . \tag{6}$$

The welding time for ½ V, V, K and X weldings are as follows for the different technologies:

SMAW = Shielded Metal Arc Welding, SMAW HR = Shielded Metal Arc Welding High Recovery, GMAW-CO$_2$ = Gas Metal Arc Welding with CO$_2$, GMAW-Mix = Gas Metal Arc Welding with Mixed Gas, FCAW = Flux Cored Arc Welding, FCAW-MC = Metal Cored Arc Welding, SSFCAW (ISW) = Self Shielded Flux Cored Arc Welding, SAW = Submerged Arc Welding, GTAW = Gas Tungsten Arc Welding

Table 2 Welding times T_{w2} (min/mm) in the function of weld size a_w (mm) for longitudinal 1/2 V and V butt welds downhand position

		1/2 V butt welds	V butt welds
Welding technology	a_w [mm]	$10^3 T_{w2} = 10^3 C_2 a_w^2$	$10^3 T_{w2} = 10^3 C_2 a_w^2$
SMAW	4-6 6-15	$3.13a_w$ $0.5214a_w^2$	$2.7a_w$ $0.45a_w^2$
SMAW HR	4-6 6-15	$2.14a_w$ $0.3567a_w^2$	$1.8462a_w$ $0.3077a_w^2$
GMAW-C	4-15	$0.2245a_w^2$	$0.1939a_w^2$
GMAW-M	4-15	$0.2157a_w^2$	$0.1861a_w^2$
FCAW	4-15	$0.1520a_w^2$	$0.1311a_w^2$
FCAW-MC	4-15	$0.2993a_w^2$	$0.2582a_w^2$
SSFCAW (ISW)	4-15	$0.1384a_w^2$	$0.1194a_w^2$
SAW	4-15	$0.1559a_w^2$	$0.1346a_w^2$

Table 3 Welding times T_{w2} (min/mm) in the function of weld size a_w (mm) for longitudinal K and X butt welds downhand position in the form $T_{w2} = \sum_i C_{2i} a_{wi}^n L_{wi}$

		K butt welds	X butt welds
Welding technology	a_w [mm]	$10^3 T_{w2} = 10^3 C_2 a_w^n$	$10^3 T_{w2} = 10^3 C_2 a_w^n$
SMAW	10-40	$0.3539a_w^{1.93}$	$0.3451a_w^{1.9}$
SMAW HR	10-40	$0.2419a_w^{1.93}$	$0.2363a_w^{1.9}$
GMAW-CO_2	10-40	$0.1520a_w^{1.94}$	$0.1496a_w^{1.9}$
GMAW-Mix	10-40	$0.1462a_w^{1.94}$	$0.1433a_w^{1.9}$
FCAW	10-40	$0.1032a_w^{1.94}$	$0.1013a_w^{1.9}$
FCAW-MC	10-40	$0.2030a_w^{1.94}$	$0.1987a_w^{1.9}$
SSFCAW (ISW)	10-40	$0.0937a_w^{1.94}$	$0.0924a_w^{1.9}$
SAW	10-40	$0.1053a_w^{1.94}$	$0.1033a_w^{1.9}$

2.2.2 Thermal and Waterjet Cutting

The four most commonly used non-contact methods of metal cutting are oxy-fuel gas, plasma, laser, and abrasive waterjet. The first three cutting processes are thermal in nature, while the waterjet method cuts by abrasive erosion. These four processes are primarily used to make precision external and interior cuts on flat sheet and plate material.

Plate cutting and edge grinding times

Oxy-fuel gas cutting, usually with acetylene gas, was once the only method of thermal cutting. The oxy-fuel torch has a pre-heating flame that heats either the iron or carbon steels to it’s "kindling temperature" of around 480º C. Then, a stream of pure oxygen is introduced causing the rapid combustion reaction between the steel and the oxygen. The resulting molten material, or slag, is blown through the metal by the stream of cutting oxygen, providing a relatively smooth and regular cut.

The calculation of the times of arc-spot welding, fabrication times of post-welding treatments, time for flattening plates, surface preparation time, painting times also can be found in Farkas, Jármai (2008).

Laser welding

The spectrum of laser welding extends from heat conduction welding to deep-penetration welding, a keyhole process in which aspect ratios of up to 10:1 are attained. High power densities permit a concentrated energy input, achieving high welding speeds as well as significantly reduced heat influence and distortion. Compared with arc welding, it allows a much wider range of materials to be welded, and material thicknesses of up to approximately 20 mm can be welded in one pass.

When compared to other welding processes, laser welding has some similar as well as some unique characteristics like GTAW (Gas Tungsten Arc Welding), laser welding is a fusion process performed under inert cover gas, where filler material is most times not added. Like electron beam welding, Laser welding is a high energy density beam process, where energy is targeted directly on the workpiece. Laser differs from both GTAW and EB (electron beam) welding in that it does not require that the workpiece complete an electrical circuit. And since electron beam welding must be performed inside a vacuum chamber, laser welding can almost always offer a cost advantage over EB in both tooling and production pricing.

One of the largest advantages that pulsed laser welding offers is the minimal amount of heat that is added during processing. The repeated "pulsing" of the beam allows cooling between each "spot" weld, resulting in a very small "heat affected zone". This makes laser welding ideal for thin sections or products that require welding near electronics or glass-to-metal seals. Low heat input, combined with an optical (not electrical) process, also means greater flexibility in tooling design and materials. The speed of laser welding of steel plates can be seen on Fig. 1, the value of welding time T [min] in the function of plate thickness t [mm].

$$S = 1/\ln T = 1/(a + bt^{2.5}) \text{ [m/min]} \tag{7}$$

$a = -0.05918578241974762$
$b = -0.02448968345282072$

where S is the welding speed [m/min], T is time [min], t is thickness [mm].

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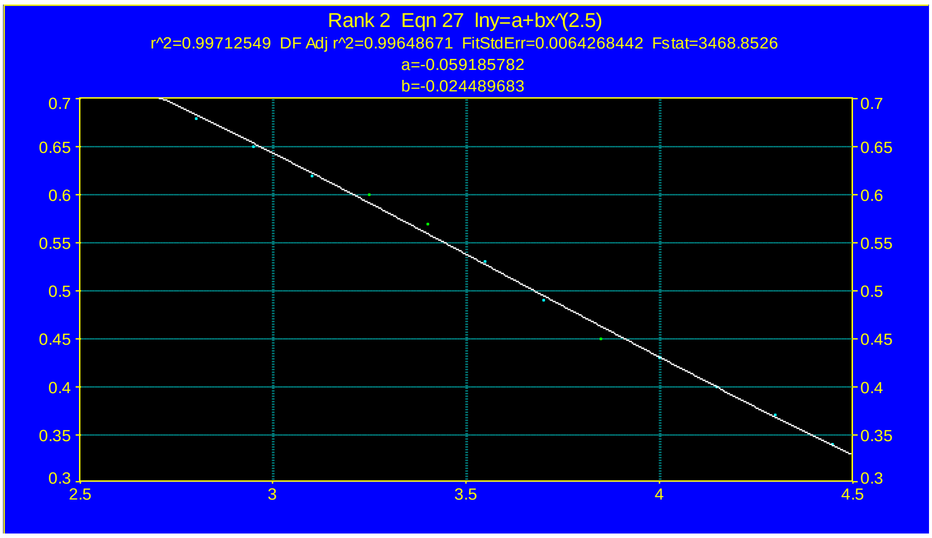

Fig. 1 Welding time *T* [min] in the function of plate thickness *t* [mm]

The cutting and edge grinding can be made by different technologies, like Acetylene, Stabilized gasmix and Propane with normal and high speed.

Table 4 Cutting time of plates, T_{CP} (min/mm) in the function of weld size a_w (mm) for fillet for longitudinal fillet welds and T-, V-, 1/2 V butt welds

Cutting technology	Thickness *t* [mm]	$10^3 T_{CP} = 10^3 C_{CP} t^n$
Acetylene (normal speed)	2-15	$1.1388 t^{0.25}$
Acetylene (high speed)	2-15	$0.9561 t^{0.25}$
Stabilized gasmix (normal speed)	2-15	$1.1906 t^{0.25}$
Stabilized gasmix (high speed)	2-15	$1.0858 t^{0.23}$
Propane (normal speed)	2-15	$1.2941 t^{0.24}$
Propane (high speed)	2-15	$1.1051 t^{0.25}$

The cutting cost function can be formulated using in the function of the thickness (*t* [mm]) and cutting length (L_c [mm]). Parameters are given in Farkas, Jármai (2008):

$$T_{CP} = \sum_i C_{CPi} t_i^n L_{ci} \ , \tag{8}$$

where t_i the thickness in [mm], L_{ci} is the cutting length in [mm]. The value of n comes from curve fitting calculations.

Table 5 Cutting time of plates for 1 mm length, T_{CP} (min/mm) in the function of weld size a_w (mm) for fillet for longitudinal X- and K butt welds

Cutting technology	Thickness t [mm]	$10^3 T_{CP} = 10^3 C_{CP} t^n$
Acetylene (normal speed)	10-40	$0.8529 t^{0.36}$
Acetylene (high speed)	10-40	$0.6911 t^{0.38}$
Stabilized gasmix (normal speed)	10-40	$0.8991 t^{0.36}$
Stabilized gasmix (high speed)	10-40	$0.6415 t^{0.44}$
Propane (normal speed)	10-40	$0.9565 t^{0.36}$
Propane (high speed)	10-40	$0.7870 t^{0.38}$

The thermal processes and the oxy-fuel gas process in particular share two disadvantages. First, heat changes the structure of metal in a "heat-affected zones" adjacent to the cut. This may degrade some metallurgical qualities at the cut's edge, requiring pre-treatment or trimming. Secondly, tolerances may be less accurate than a machined cut, except for laser cutting.

Laser cutting of steel (Fig. 2) and aluminium (Fig. 3)

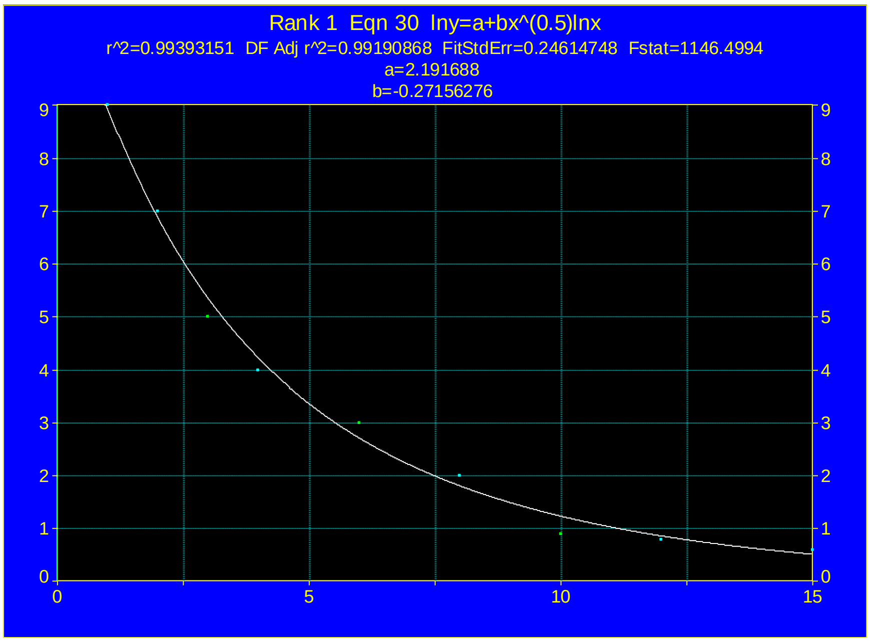

Fig. 2 Steel sheet cutting [time/thickness]

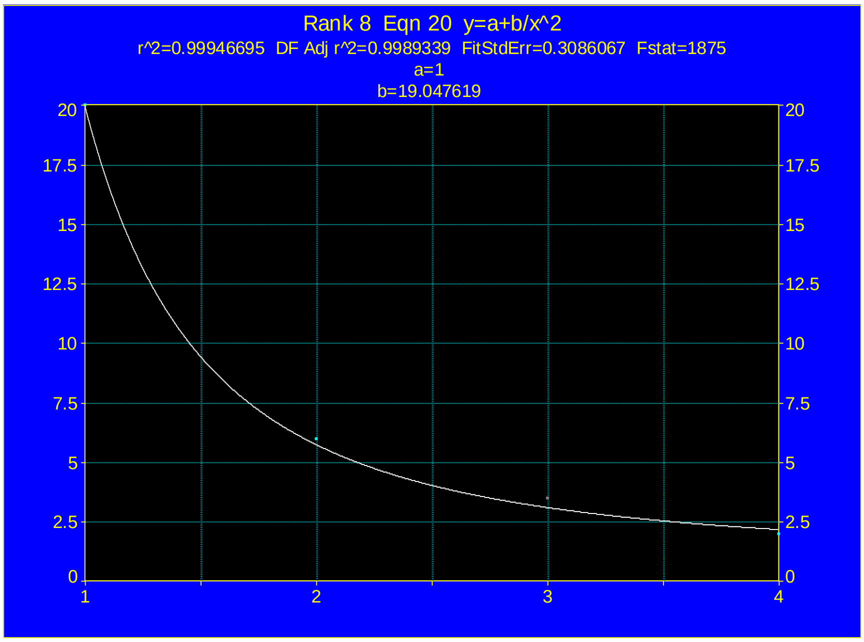

Fig. 3. Aluminium sheet cutting [time/thickness]

Laser cutting of steel sheets	*Laser cutting of aluminium sheets*	
$S=1/\ln T=1/(a+bt^{0.5}\ln t)$ [min/m]	$S=1/T=1/(a+b/t^2)$[min/m]	(9)
$a=2.191688010897978$	$a=1$	
$b=-0.2715627600304911$	$b=19.04761904761905$	

Laser cutting is a fairly new technology that allows metals and some non metallic materials to be cut with extreme precision if required. The laser beam is typically 0.2 mm in diameter with a power of 1-2 kW. At laser cutting process, a beam of high-density light energy is focused through a tiny hole of the nozzle. When this beam strikes the surface of the work piece, the material of the work piece is cut immediately. Lasers work best on materials such as carbon and stainless steels. Metals such as aluminium and copper alloys are more difficult to cut by laser due to their ability to reflect the laser light as well as absorb and conduct heat. The distribution of the application of laser in different manufacturing processes can be seen on Fig. 4. Laser cutting is the largest application.

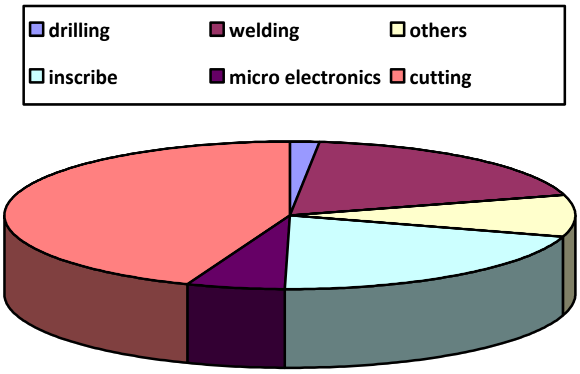

Fig. 4 Distribution of the application of laser in different manufacturing processes

Waterjet cutting of steel (Fig. 5) and stainless steel (Fig. 6)

A water jet cutter is capable of cutting a wide variety of materials using a very high-pressure jet of water, or a mixture of water and an abrasive substance.

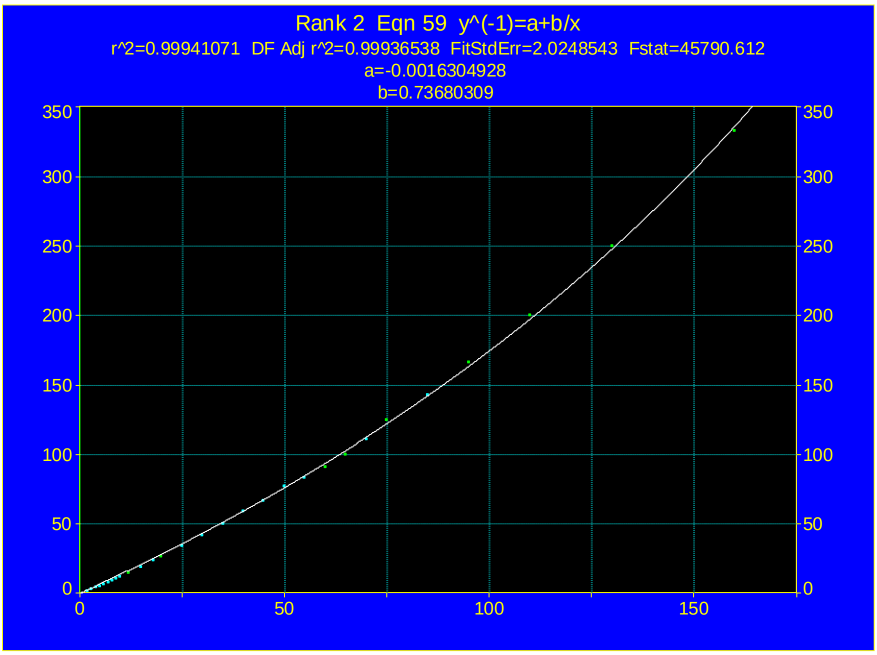

Fig. 5 Steel sheet cutting [time/thickness]

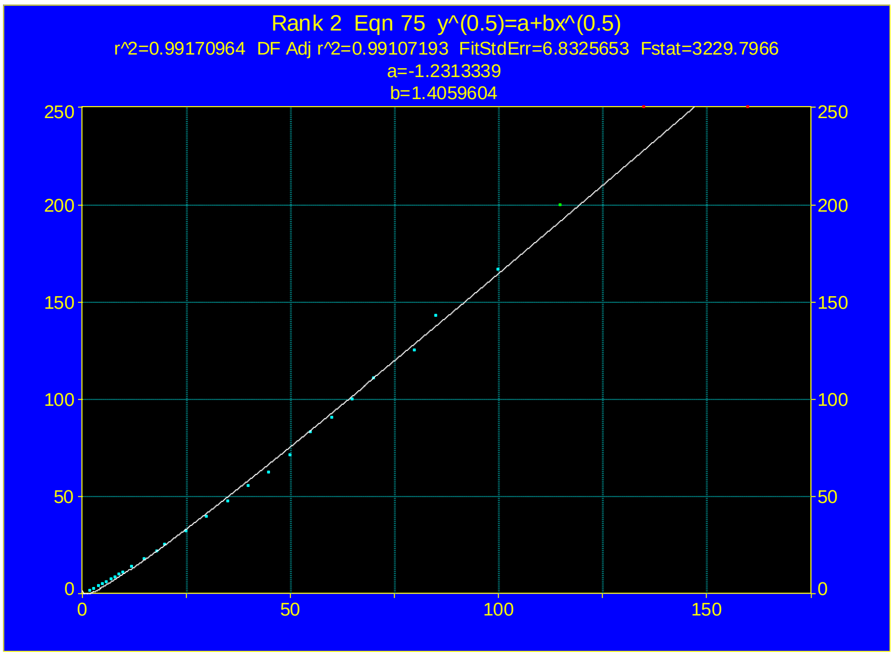

Fig. 6 Stainless sheet cutting [time/thickness]

Waterjet cutting, carbon steel 3500 bar	*Waterjet cutting stainless steel pressure 3500 bar*	
$S= 1/T=a+b/t$ [m/min]	$S=1/T^{0.5}=1/(a+bt^{0.5})$[m/min]	(10)
a= -0.001630492750216705	a= -1.231333913075542	
b= 0.7368030917264656	b= 1.405960445076508	

Plasma cutting of steel (Fig. 7) and stainless steel (Fig. 8)

Plasma cutting uses an extremely high temperature, high velocity stream of ionized gas to cut the metal. Plasma temperatures range from about 5500 ºC to 28,000 ºC. Depending upon the material to be plasma cut, the gases used include: standard compressed shop air, oxygen, argon and hydrogen, or nitrogen and hydrogen. Gas shielding is accomplished with air, water, or carbon dioxide.

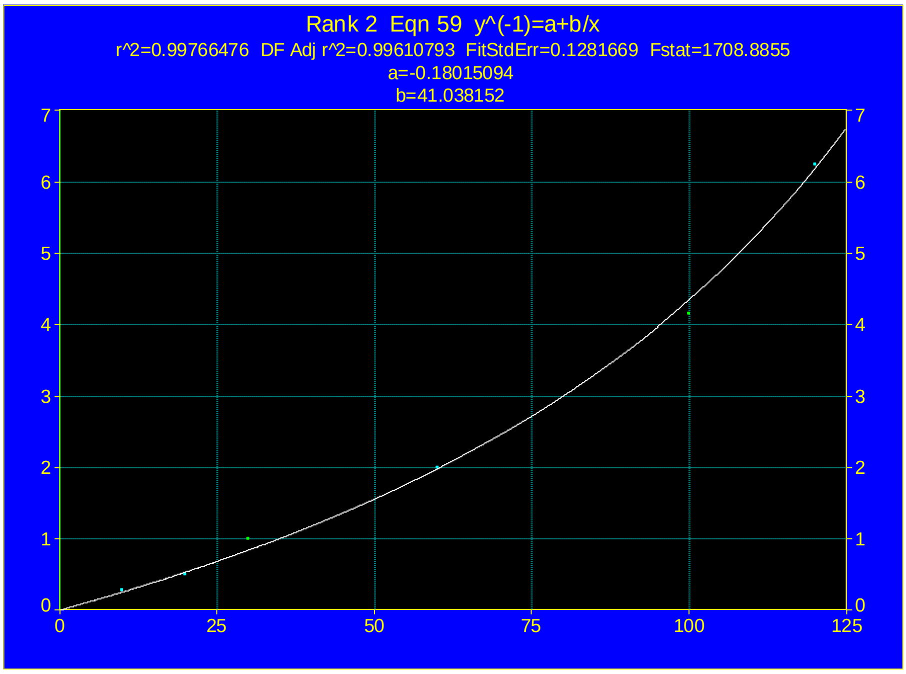

Fig. 7 Steel sheet cutting [time/thickness]

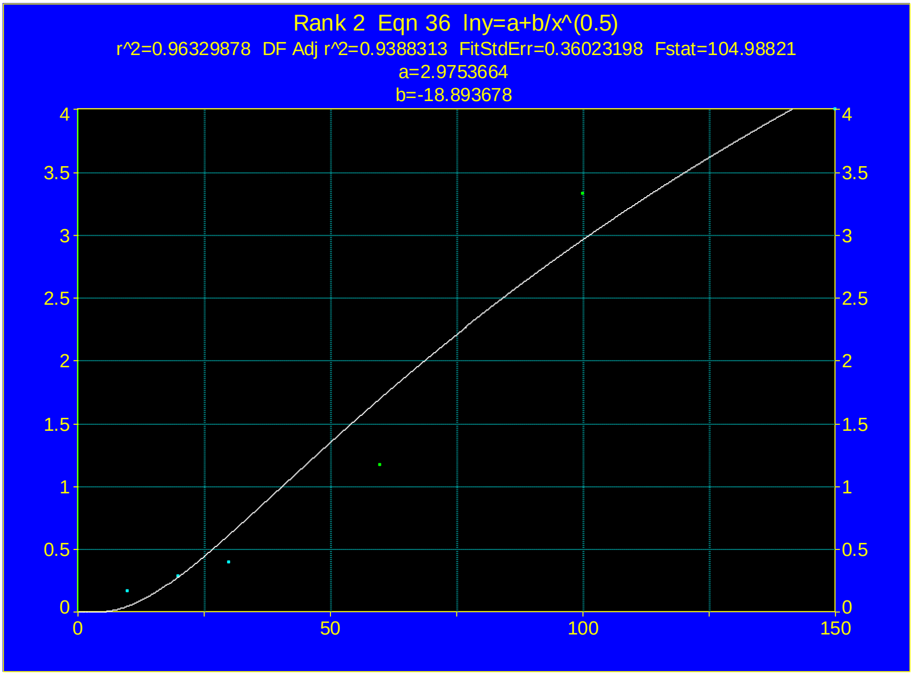

Fig. 8 Stainless sheet cutting [time/thickness]

Plasma cutting requires a torch, a power supply, and an arc-starting circuit. The plasma cutting power supply is a constant-current DC power source. A high frequency AC starting circuit ionizes the gas to make it conductive. When gas is fed to the torch, part of the gas is ionized by the high-voltage arc starter between the electrode, or cathode, in the torch, and the torch tip. When the power supply's small DC current meets this high voltage gas, it creates a pilot arc. This pilot arc leaves the torch tip as a plasma jet and becomes the path for the main plasma arc. Once the pilot arc contacts the metal's surface, or anode, the main arc forms. The pilot arc then shuts off, and the cutting torch beings operation.

Plasma cutting of stainless steel	*Plasma cutting of aluminium*	
$S=1/T=a+b/t$ [m/min]	$S=1/\ln T=1/(a+b/t^{0.5})$ [m/min]	(11)
a= -0.1801509431963638	a= 2.97536641707248	
b= 41.03815214608195	b= -18.8936784318449	

2.2.3 Time for flattening plates

$$T_{FP}=\Theta_{df}\left(a_e+b_e t^3+\frac{1}{a_e t^4}\right)A_p\,, \tag{12}$$

where a_e=9.2x10^{-4} min/mm^2, b_e= 4.15x10^{-7} min/mm^5, Θ_{df} is the difficulty parameter (Θ_{df} = 1,2 or 3). The difficulty parameter depends on the form of the plate.

2.2.4 Surface preparation time

The surface preparation means the surface cleaning, sand spraying, etc. The surface cleaning time can be defined in the function of the surface area (A_s [mm^2]) as follows:

$$T_{SP}=\Theta_{ds}a_{sp}A_s\,, \tag{13}$$

where a_{sp} = 3x10^{-6} min/mm^2, Θ_{ds} is a difficulty parameter.

2.2.5 Painting time

The painting means making the ground- and the topcoat. The painting time can be given in the function of the surface area (A_s [mm^2]) as follows:

$$T_P=\Theta_{dp}(a_{gc}+a_{tc})A_s\,, \tag{14}$$

where a_{gc} = 3x10^{-6} min/mm^2 , a_{tc} = 4.15x10^{-6} min/mm^2, Θ_{dp} is a difficulty factor, Θ_{dp}=1,2 or 3 for horizontal, vertical or overhead painting. Tizani et al. (1996) proposed a value for painting 14.4 x10^{-6} \$/mm^2. For more complicated structures we use k_P = 2x14.4x10^{-6} \$/mm^2.

2.2.6 Times of hand cutting and machine grinding of strut ends

At tubular structures a main part of the total cost is the cost of hand cutting and machine grinding of strut ends. We use the following formula (Farkas & Jármai 2008). Glijnis (1999) proposed a formula for one strut end in the case of oxyfuel cutting on CNC machine as follows:

$$K_{CG}(\$) = \frac{2.5\pi d_i}{(350 - 2t_i)0.3\sin\varphi_i}, \tag{15}$$

where 350 mm/min is the cutting speed, 0.3 is the efficiency factor, d_i and t_i are in mm.

2.2.7 Cost of intumescent painting

Intumescent paintings are getting more and more popular, because they look attractive, does not have a bad effect on slim steel structure view, but the painting is relatively expensive

$$K_{pi} = (k_p + k_{pi})\,A_p, \tag{16}$$

where the specific painting cost k_p = 14 \$/m^2 , means the normal painting in two layers (ground and top coat). The additional intumescent painting cost depends on its thickness. The thickness is proportional to the protection time. The cost is k_{pi} = 20 \$/m^2, for R30, half hour, or k_{pi} = 60 \$/m^2 for R60, one hour protection. A_p is the full covered surface.

2.3 Total cost function

The total cost function can be formulated by adding the previous cost functions together (depending on the structure some can be zero).

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m}\left(T_{w1} + T_{w2} + T_{w3} + T_{FP} + T_{SP} + T_P + T_{CG} + \ldots\right) + \frac{K_{pi}}{k_m} + \ldots + \tag{17}$$

Taking k_m = 0.5-1.5 \$/kg, k_f =0 -1 \$/min. The k_f/k_m ratio varies between 0 - 2 kg/min. If k_f/k_m = 0, then we get the mass minimum. If k_f/k_m = 2.0 it means a very high labour cost (Japan, USA), k_f/k_m = 1.5 and 1.0 means a West European labour cost, k_f/k_m = 0.5 means the labour cost of developing countries. Even if the production rate is similar for these cases, the difference between costs due to the different labour costs is significant.

3 CONCLUSION

When we consider the interaction of design and technology, we should not forget the cost of the structure as the third leg of the system. These three together help us to find the best solution. These cost calculations are founded on material costs and those fabrication costs, which have direct effect on the sizes, dimensions or shape of the structure.

In this paper the cost calculation of different welding, cutting, painting, etc. technologies have been described. These cost calculations are founded on material costs and those fabrication costs, which have direct effect on the sizes, dimensions or shape of the structure. The calculated times for different newer technologies like

laser, plasma, waterjet, etc. have been included also. In the design phase we can choose the best technology available for the production.
Cost and production time data come from different companies from all over the world. When we compare the same design at different countries, we should consider the differences between labour costs. It has the greatest impact on the structure sizes, when the technology is the same.

Acknownledgements

The research was supported by the TÁMOP 4.2.4.A/2-11-1-2012-0001 priority project entitled ‘National Excellence Program - Development and operation of domestic personnel support system for students and researchers, implemented within the framework of a convergence program, supported by the European Union, co-financed by the European Social Fund. The research was supported also by the Hungarian Scientific Research Fund OTKA T 109860 project and was partially carried out in the framework of the Center of Excellence of Innovative Engineering Design and Technologies at the University of Miskolc.

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