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https://doi.org/10.21278/TOF.462039122
ISSN 1333-1124
eISSN 1849-1391

A COMPARISON OF WELDED STRUCTURE COST CALCULATION METHODS

Summary

With the increase in material and labour costs, the optimization of welded steel structures is gradually becoming a necessity. Precise cost calculation methods are a prerequisite for the optimization process; they enable the designers to differentiate between product variations and select the best one. However, while the calculation of the material cost is simple, the calculation of fabrication costs, which include the costs of cutting, handling, welding, and surface preparation, is harder to define. Thus, in this paper, two available cost calculation methods are compared by observing two specific welded structures: a welded I beam and a gearbox housing. Both the total and the partial costs were compared. Based on the results, it was concluded that the methods are in agreement considering the total cost values and that both methods can differentiate between the design variations comparably. On the other hand, partial costs of process segments differed, mostly due to variations in the pre-defined scope of each process (e.g., one method included handling in the material costs, while the other included it in the welding costs).

Key words: *cost calculation; welded structure; beam; gearbox housing; optimization*

1. Introduction

The product development process traditionally consists of sequential (and partially overlapping) phases – planning, conceptual phase, design phase, detailing, analysis/validation, and finally, preparation for manufacturing [1]. Even though there are iterative elements to the process, returning to previous phases is often reserved for the initial phases (planning, concept design), mostly to avoid increasing costs [2]. In other words, once the design is finalised and tested, engineers are unlikely to revise it to reduce material costs and energy consumption (with the exception of mass production). After analysing seventy-nine steel-framed buildings, Moynihan and Allwood concluded that 46% of the steel mass in beams and columns is not load bearing [3]. Similarly, when designing steel structures, the primary task is to ensure their viability; the structure must meet both the stability and strength criteria. Once the structure is deemed valid, it is necessary to ensure that it is manufactured according to the specification. Additionally, manufacturing technologies and associated costs will often pre-define the shape of some structure segments. Thus, the resulting structures are often ineffective regarding both the material and manufacturing costs [4].

Due to the wide application of steel structures, the need for optimization is clear in both civil engineering and mechanical engineering. Since the excessive steel mass in structural frames is mostly a result of reluctance to approach the expected load capacity, there is room for improvement [5]. By reducing the material and energy-related costs, it is possible to increase industrial sustainability, thus providing multiple benefits. However, to do that, it is necessary to estimate the final costs during the initial design phases. Cost calculation methods enable practitioners to explore a greater number of potential designs by applying optimization algorithms. The cost calculation methods should be simple in order to minimize the time added to the development process. Contemporary cost calculation methods have a high level of utility in both research and practice. Hayalioglu and Degertekin [6] applied the cost calculation method proposed by Xu and Grierson [7] aiming to find minimum cost steel frame design. Based on what has been stated so far, it can be concluded that correct presentation of relative differences between the costs of design variants is of vital importance because this increases the quality of optimization process outputs [8].

As shown in the previous section, several cost calculation methods are available. Jármai and Farkas [9] proposed a cost calculation function that considered the time required for welding, plate flattening, surface preparation, cutting, electrode changing, delagging, and painting. However, the authors noted that while the resulting times are general, the associated costs largely depend on the economic development of the country. Thus, the specific ratio between the fabrication and the material costs reduced the effect of the proposed cost calculation function. Heinisuo et al. [10] developed a cost estimation method based on the building information models (BIMs); product costs were estimated based on the product features. Similar to the study by Jármai and Farkas, structure erection and transportation costs were not considered. Haapio [11] proposed a more comprehensive method by including more detailed effects of joint costs. Additionally, the structure erection and transportation costs were included. The method accuracy was verified by comparing the calculated costs for eight products with the quotes from five manufacturers. The method proposed by Haapio was further developed by Mela and Heinsuo [12].

The initial study on the cost calculation methods conducted by the authors of this paper has shown that there are variations in the outcomes of the studied methods; this showed a need for a more detailed study. Thus, in this article, the available cost calculation methods are reviewed; the methods are compared both at the global (total outcome value) and the component level (for example, assessed cutting costs). The comparison was carried out in two steps. First, two example cases, i.e. a welded steel beam and a gearbox housing, were used to determine variations in outcomes. In the second step, each of the calculation methods was used as an objective function in an optimization process to study its influence on the resulting parameters. The study presented here is organised as follows: research methodology and a brief overview of each method are given in Section 2; the two example cases are presented in detail in Section 3; the results and the differences between the methods are presented and discussed in Section 4. Finally, conclusions are given in a separate section, Section 5.

2. Methods

Two available cost calculation methods were used to determine the costs of two steel structures, which allowed us to compare their efficiency and effectiveness. Similar to the research presented by Ananthi et al. [13], our study was designed as a parametric study to encompass the effects of plate dimensions and thicknesses on the costs. Thus, nine variants were generated for each of the structures; three size levels and three plate thickness levels were varied. The cost calculation methods used are presented below.

2.1 Cost calculation method presented by Jármai and Farkas (the Jármai-Farkas method).

The cost calculation method presented by Jármai and Farkas [9] remains relevant and is widely accepted by researchers. The method is only briefly outlined in this section; for more details, please see the original paper [9]. It should also be noted that the method was also published with additional details in [14], while the latest version was published by Jármai in 2018 [15]. In this paper, we used the latest edition of the method, which omits the problematic surface flattening time used in the previous versions. The output currency used is the US dollar ($). It should be noted that currency exchange rates (USD-EUR) and associated effects are not considered in this paper.

The presented cost function includes the material and fabrication costs which are joined through corresponding cost factors k_m and k_f; it is given as

$$K = k_\mathrm{m}\rho V + k_\mathrm{f}\overbrace{\left(T_1 + T_2 + T_3 + T_4 + T_5 + T_6 + T_7\right)}^{\Sigma T_\mathrm{i}} \tag{1}$$

where ρ [kg/m^3] is the material density, V [m^3] is the total volume of required material, and ΣT_i [s] is the total production time. In this paper, values of fabrication and material factors were taken as $k_m = k_f = 1$, which, in the opinion of the authors of this study, represents the West European labour cost. The total production time consists of seven components; the first one is the preparation time T_1, which includes assembly and tacking:

$$T_1 = C_1 \cdot \Theta_\mathrm{d} \cdot \sqrt{\kappa\rho V} \tag{2}$$

The preparation time greatly depends on the difficulty factor Θ_d, whose values are given; it depends on the characteristics of the structure (planar or spatial) and the weld (length, type, welding position, and welded part geometry). Furthermore, besides the number of parts κ, material density ρ, and volume V, the preparation time T_1 is affected by the value of constant C_1. The process of constant C_1 value selection is not discussed here; the authors used $C_1 = 1$.

The welding time T_2 and associated fabrication operations T_3 (replacing the electrodes, delagging, and chipping) are calculated as follows:

$$T_2 + T_3 = 1.3\sum_{i=1}^{n} C_{2\mathrm{i}} a_{\mathrm{wi}}^{m} L_{\mathrm{wi}}\ , \tag{3}$$

where a_{wi} is the weld size, L_{wi} is the weld length, and C_{2i} [min/mm$^{2.5}$] is the welding technology constant. The values of C_2 proposed by the authors were: 0.0008 for manual-arc welding and 0.0005 for CO_2 welding. The weld size a_{wi} is raised to the power of m, which depends on the welding technology; in this paper, shielded metal arc welding was assumed, for which $m = 2$.

Furthermore, the time required to flatten the plates (T_4) is defined as

$$T_4 = \Theta_\mathrm{de}\left(a_\mathrm{e} + b_\mathrm{e} t^3 + \frac{1}{a_\mathrm{e} t^4}\right) A_\mathrm{p}\ , \tag{4}$$

where a_e [mm] is the plate thickness and Θ_{de} the difficulty factor equal to 1, 2, or 3, which depends on the plate form; no further guidelines were provided. It should be noted that plate flattening times were not considered in this paper as it was assumed that the plates bought from the supplier were flat (the same assumption is made in the method presented by Mela and Heinisuo).

The surface preparation (T_5) and the painting time (T_6) mostly depend on the total surface area A_s, which is multiplied by the difficulty factors Θ_{ds} and Θ_{dp}, respectively. The difficulty factor value is equal to 1 for the horizontal, 2 for the vertical, and 3 for the overhead painting/surface preparation. Factors a_{sp}, a_{gc}, and a_{tc} are constants provided by the authors. The expression for the surface preparation and the painting time can be written as follows:

$$T_5 + T_6 = \overbrace{\Theta_{\mathrm{ds}} a_{\mathrm{sp}} A_{\mathrm{s}}}^{\text{Suraface prep.}} + \overbrace{\Theta_{\mathrm{dp}} \left(a_{\mathrm{gc}} + a_{\mathrm{tc}} \right) A_{\mathrm{s}}}^{\text{Painting}} \tag{5}$$

Finally, the cutting and edge grinding time (T_7) was also included in the assessment. It is affected by the manufacturing technology (factor C_7) and the plate thickness (t_i):

$$T_7 = \sum_i C_{7\mathrm{i}} t_{\mathrm{i}}^{\mathrm{n}} L_{\mathrm{ci}} \tag{6}$$

2.2 Cost calculation method presented by Mela and Heinisuo (the Mela-Heinisuo method)

Similar to the method presented by Jarmai and Farkas, Mela and Heinisuo [12] divided the manufacturing process into smaller segments. It should be added that their method also includes the research done by Haapio [11]. For each of the segments, the authors accounted for the costs of material, labour, energy, and time. This cost calculation method is primarily intended for steel beams. The cost function is defined as:

$$C(\mathbf{x}) = C_{\mathrm{M}}(\mathbf{x}) + C_{\mathrm{B}}(\mathbf{x}) + C_{\mathrm{C}}(\mathbf{x}) + C_{\mathrm{S}}(\mathbf{x}) + C_{W}(\mathbf{x}) + C_{\mathrm{P}}(\mathbf{x}) + C_{\mathrm{T}}(\mathbf{x}) + C_{\mathrm{E}}(\mathbf{x}) \tag{7}$$

The method also includes the beam transportation (C_T) and erection (C_E) costs, which were not included in the method of Jarmai and Farkas nor in this study.

In addition to the costs of beam transportation and erection (C_T and C_E), equation (7) includes the costs of material, blasting, cutting, welding, and painting. Material costs C_M include the steel volume and grade; for the S355 steel used in this paper, volume is multiplied by the cost factor $K_M = 1$. After including the known constants, the final material cost was calculated as $0.7K_MV$.

Blasting costs C_B were defined only for the total beam length; therefore, the calculation of blasting costs for other products is made difficult. Thus, for the gearbox segment housing presented in Section 3.2, the total length of the plates L_{pl} was used instead of the total beam length:

$$C_{\mathrm{B}}(\mathbf{x}) = 3 \cdot 3.64 \cdot 10^{-4} L_{\mathrm{pl}} \tag{8}$$

Cutting costs C_C were defined for both the non-productive and productive times. The non-productive time was taken as 3 min, while the productive time depended on the cutting technology, plate thickness, and the total length of cuts. The costs of consumables were taken as 0.38 EUR/min, while the energy cost was 0.12 EUR/min; both values were provided in [12]:

$$\begin{gathered} C_{\mathrm{C}}(\mathbf{x}) = \sum_{i=1,2} 1.32\big(3 + T_{\mathrm{PCui}}(\mathbf{x})\big) + T_{\mathrm{PCui}}(\mathbf{x})\Big[0.22 + 4.18\Big(10 - 5t_i^2 + 0.001t_{\mathrm{i}} + 0.0224\Big)\Big]; \\ \text{where: } T_{\mathrm{PCui}}(\mathbf{x}) = \frac{L_{\mathrm{Cui}}(\mathbf{x})}{8.92t_{\mathrm{i}}^2 - 486.87t_{\mathrm{i}} + 8115.8} \end{gathered} \tag{9}$$

In the expressions (9), i represents the plate thickness group. In the cases considered in this paper, two thicknesses were used; thus, $i = 1, 2$.

Welding costs C_W include the productive and non-productive times. The productive time is calculated as a function of weld length, size, and steel grade. It should also be noted that the method was developed for producing welded beams; thus, it was assumed that the web and flange would be connected via fillet welds. It was assumed that both fillet weld sides were produced in one go. For this reason, it was necessary to adjust the method so it could be applied to other welded products. In this paper, fillet welds were also used and the same assumption was made; consequently, the total fillet weld length was divided by 2. Finally, the welding cost was expressed as

$$C_W(\mathbf{x}) = 1.36\left(6.25 + T_{\mathrm{PBW}}(\mathbf{x})\right) + 1.44 T_{\mathrm{PBW}}(\mathbf{x})$$
$$\text{where:} \quad T_{\mathrm{PBW}}(\mathbf{x}) = \frac{7.85 \cdot 10^{-6} L_{\mathrm{w}} a_{\mathrm{w}}^{2}}{14} \tag{10}$$

Finally, painting costs C_P were calculated as a function of the painted area. In addition to the painting itself, drying costs were also considered:

$$C_{\mathrm{P}}(\mathbf{x}) = \overbrace{4.17 \cdot 10^{-6} A_{\mathrm{u}}(x)}^{\text{painting}} + \overbrace{0.36 LB}^{\text{drying}} , \tag{11}$$

where A_{u} represents the total area to be painted.

3. Case study models and their properties

The cost calculation methods were compared using two example cases – a welded I beam with web openings and a gearbox housing segment (see **Fig. 1**). The former was selected because steel beam structures are regularly subjected to optimization; therefore, accurate cost calculation will increase the quality of results. Additionally, most of the cost calculation methods have been devised to assess the cost of such structures. The flanges and the web of the welded I beam studied here are joined via fillet welds and the web openings are used to reduce the structure weight.

The gearbox housing segment is a completely different problem. This case was selected to investigate whether the relations between the outputs of the welded I beam cost calculation methods would change with the problem complexity. Compared to the welded I beam, the gearbox housing has a larger number of parts and welds on one hand, but it requires less material on the other. Thus, it is expected from the cost calculation methods to highlight the effects of handling, welding, and positioning times. It should also be noted that bearing mounting times were not incorporated since the cost calculation methods generally do not consider turning and milling operations.

For each example, costs were calculated for nine variations on the basic structure. The nine variations included changes in outer dimensions, as well as variations in the thickness of plates used to create the product. Three levels of plate thickness (including the weld sizes) and three levels of outer dimensions were considered.

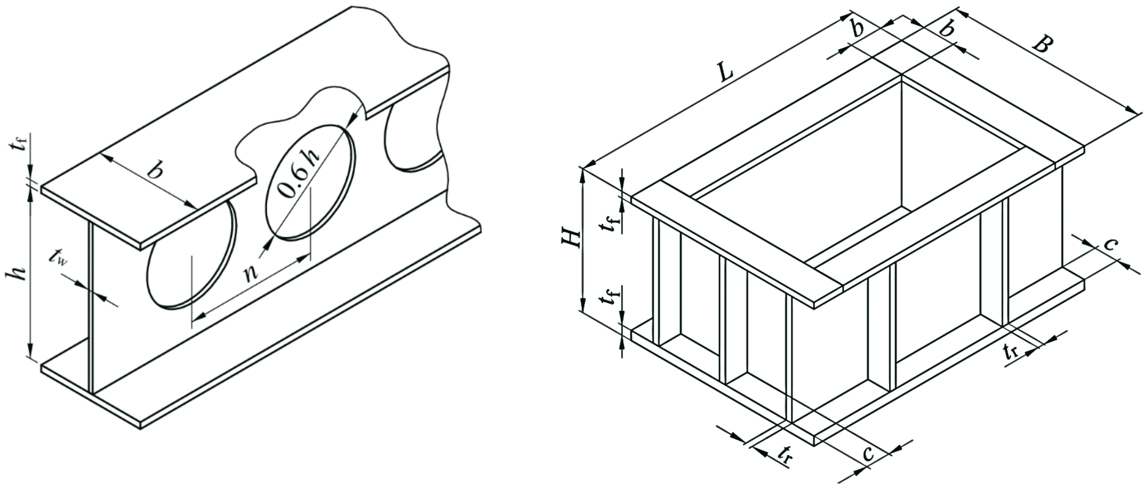

Fig. 1 Schematic drawings of a welded I beam (left) and a gearbox housing segment (right)

3.1 Welded I beam

Variations in the welded I beam are given in **Table 1**; they were obtained by combining three plate thickness levels and three outer dimension levels. In addition to changing the plate thickness, the weld height *a* was also varied as larger welds would be required for more robust specimens. Further, it was assumed that the beam would be made of structural steel (S355JR), with a density of 7850 kg/m^3. To reduce the beam weight, circular openings were made in the web; the number of openings *n* was varied with the beam length. The value of factor accounting for the difference between the fabrication and material costs was taken as 1 for both methods. It was also assumed that after flame cutting (acetylene was used as fuel), the plate surfaces would be prepared for welding and subsequent painting. It should be noted that, when determining the cut length for each part, the parts of the same thickness were grouped together to minimize the total cut length. Manual arc welding was used to join the plates.

Table 1 Data for the welded I beam and the gearbox housing segment

Variation	**I-1**	**I-2**	**I-3**	**I-4**	**I-5**	**I-6**	**I-7**	**I-8**	**I-9**
Length, *L* / mm	5000	7500	10000	5000	7500	10000	5000	7500	10000
Width, *b* / mm	200	250	300	200	250	300	200	250	300
Height, *h* / mm	300	400	500	300	400	500	300	400	500
Flange thickness, t_b / mm	10	10	10	15	15	15	20	20	20
Web thickness, t_h / mm	6	6	6	10	10	10	14	14	14
Weld height, *a* / mm	4	4	4	5	5	5	6	6	6
Number of web openings, *n* / -	16	22	28	16	22	28	16	22	28
Variation	**II-1**	**II-2**	**II-3**	**II-4**	**II-5**	**II-6**	**II-7**	**II-8**	**II-9**
Length, *L* / mm	320	370	420	320	370	420	320	370	420
Width, *b* / mm	220	250	280	220	250	280	220	250	280
Height, *h* / mm	140	170	200	140	170	200	140	170	200
Rib/wall thickness, t_r / mm	6	6	6	8	8	8	10	10	10
Flange thickness, t_f / mm	8	8	8	10	10	10	12	12	12
Weld height, *a* / mm	3	3	3	4	4	4	5	5	5
Flange width, *b* / mm	35	40	50	35	40	50	35	40	50
Wall position, *c* / mm	25	30	40	25	30	40	25	30	40

3.2 Gearbox housing segment

The gearbox housing was selected as the second case and the associated variations are provided in **Table 1**. As in the previous case, nine variations were created and divided into three groups. Both the outer dimensions and plate thicknesses were varied. The first group (II-1 to II-3) included gearbox housing segments made of 6 mm and 8 mm thick plates, the second group (II-4 to II-6) of 8 mm and 10 mm thick plates, and the third group (II-7 to II-9) of 10 mm and 12 mm thick plates. The wall thicknesses were smaller than flange thicknesses and weld dimensions were determined based on the wall thickness (thicker welds were used for thicker walls). Additionally, plates were welded on both sides and corner welds were used. The outer dimensions were also varied. Variations II-1, II-4, and II-7 represented the smallest housings, variations II-2, II-5, and II-8 the middle-sized housings, while variations II-3, II-6, and II-9 the largest housings.

4. Results and discussion

Once the cases were fully defined, both cost calculation methods were applied to all the variations. Final costs were calculated and compared for both cases to enable the comparison of the methods. In the text below, the results are presented separately for each case to enable an in-depth comparison. That way, it was possible to compare the share of each partial cost, such as that of the material, welding, or painting in the total value.

4.1 Total cost values

From the optimization point of view, it is important that a method outlines the differences between similar designs and denotes the higher-quality one (in this case, the one with lower costs). Thus, it was important to determine whether the investigated methods would capture the differences between the design variations in the same manner. It should be added that the outputs of the two methods differed; while the method proposed by Mela and Heinisuo provided costs in EUR, the one proposed by Jarmai and Farkas resulted in a dimensionless value. The dimensionless value included both the material and the fabrication costs.

The results for both cases are shown in **Fig. 2**. When observing solely the welded I beam, the results obtained using the two methods were in good agreement. The largest difference was calculated for case I-7, for which the Mela-Heinisuo method calculated a 14% lower value compared to that calculated by the Jarmai-Farkas method. Generally, the latter method yielded higher values, with the exception of case I-6. While it was rather easy to differentiate between the cases with length differences (I-1 to I-3; I-4 to I-6, and I-7 to I-9), it was more difficult to differentiate between the cases I-1, I-4, and I-7. The differences were smaller, but both methods provided the same relations between the respective values.

When considering the gearbox housing segment, the methods produced similar results, but more varied compared to the welded I beam case. Most significant differences were noted in cases II-7, II-8, and II-9, which had the largest plate thicknesses. For those cases, the method proposed by Jarmai and Farkas resulted in higher total costs. The largest difference was found for variation I-9, for which the cost predicted by the Mela-Heinisuo method was 15.6% lower. It can also be seen that the costs for cases II-2 and II-4 were rather close, but both methods identified the II-4 case as costlier.

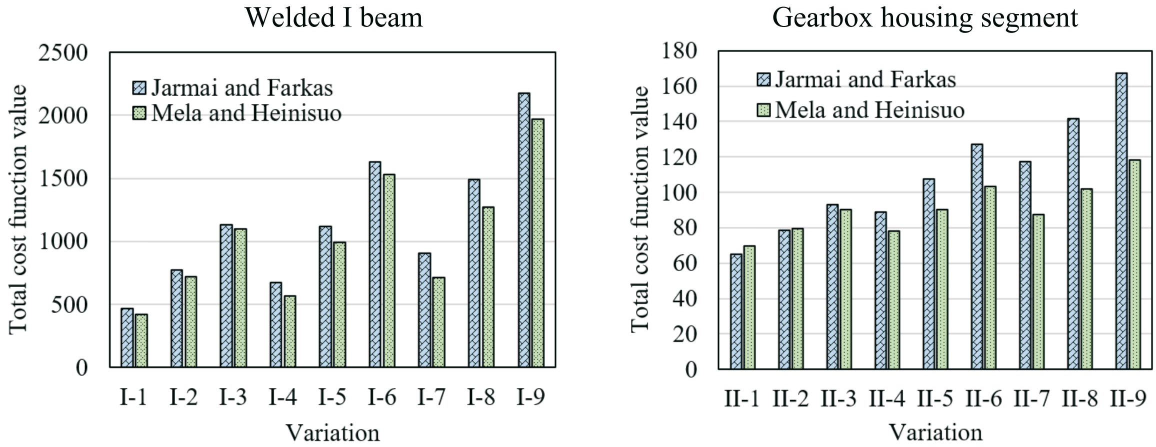

Fig. 2 Comparison between the total cost function values obtained by two methods

The results obtained for the welded I beam were compared to those for the gearbox housing segment. As expected, the total values are much higher for the welded I beam due to much larger dimensions. Considering the ability to distinguish between the variations, it was concluded that the methods are in agreement and could be used as objective functions in the optimization process. This confirms the findings presented in [16] where the authors showed that regardless of the cost calculation method, the optimization process would yield the same configuration of the welded I beam in question.

4.2 Welded I beam

The partial costs of each fabrication process and of the material, obtained by the two cost calculation methods, were compared next. As shown in **Fig. 3**, in the Mela-Heinisuo method, the share of material cost in the total cost was bigger than in the Jarmai-Farkas method. This was a direct result of higher overall costs obtained by the Jarmai-Farkas method since the predicted material costs were the same for both methods.

Further, the Jarmai-Farkas method predicted lower cutting costs; the highest share of cutting costs, i.e. 10.2%, was obtained for case I-1, compared to 29.5% predicted by the Mela-Heinisuo method. As outer dimensions and plate thicknesses increased, the share of welding costs decreased. For both methods, a change in plate thickness had a stronger effect on the share of welding costs than a change in outer dimensions. Regarding the share of surface preparation costs, it ranged from 1.6% to 3.3%, and from 0.6% to 1.3% for the Jarmai-Farkas and the Mela-Heinisuo method, respectively. In the Jarmai-Farkas method, higher values were obtained for larger specimens, while the opposite was true for the Mela-Heinisuo method.

When considering welding costs, the Jarmai-Farkas method yielded significantly higher values. A share of welding costs in the total cost ranged between 35.9% (I-3) and 50.6% (I-7). Obviously, the increase occurred primarily due to the increase in weld size. When considering changes in outer dimensions, an increase in dimensions generally decreased the share of welding costs since the material costs were increased. The same trend was noticed in the Mela-Heinisuo method, but with a much lower total share value, ranging between 6.12% (I-3) and 10.29% (I-7), than in the Jarmai-Farkas method.

Finally, the share of painting costs in the total cost was similar in both methods and it increased with an increase in the total area to be painted.

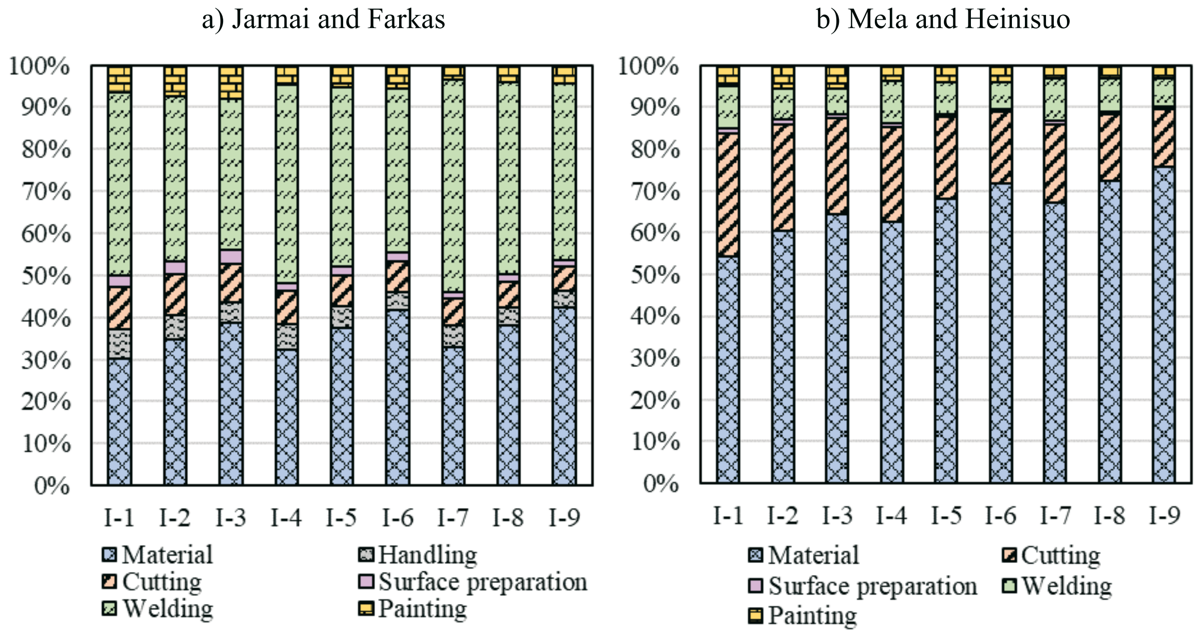

Fig. 3 Shares of partial fabrication and material costs in the total cost for the welded I beam

4.3 Gearbox housing segment

The gearbox housing segment was considered next. Compared to the welded I beam outlined in Section 4.2, it is evident that the distributions of partial gearbox housing costs obtained by the two methods are in better agreement. Shares of painting, surface preparation, and welding costs in the total cost were roughly the same, while the shares of material, cutting, and handling costs differed. Further, when comparing the material costs obtained by the two methods, the Mela-Heinisuo method predicted that the material costs would take a larger share. The share of material costs in the total costs ranged between 10.6% (II-7) and 15.8% (II-3) in the Jarmai-Farkas method, and from 18.9% (II-1) and 30.9% (II-9) in that of Mela and Heinisuo. It should be pointed out once again that material costs are equal in both methods and increase linearly with volume.

Further, according to the Jarmai-Farkas method, handling costs take a significant share in the total costs. The largest share of handling costs, i.e. 33.6%, was calculated for variation II-1. This is caused mostly by a larger number of parts (15 compared to 3 in the welded I beam case), which should be positioned correctly before welding. In addition, the gearbox housing geometry is more complex than that of the welded I beam, which requires a higher level of difficulty factor. The difference in the share of cutting costs is more notable compared to the welded I beam case; it is roughly 5 to 6 times higher when calculated by the Mela-Heinisuo method. When further considering the structure of cutting costs calculated by this method, consumables accounted for a rather small share, roughly 3% of the total cost, while the non-productive time accounted for one-third of cutting costs.

The share of welding costs calculated by the Jarmai-Farkas method was larger than that calculated by the Mela-Heinisuo method, which is in agreement with the values obtained for the welded I beam. As shown in **Fig. 4**, welding costs take the largest share in the total production costs. However, the difference between the outputs produced by the two methods in this regard was significantly smaller compared to the welded I beam case. Further, in the Jarmai-Farkas method, welding costs were exclusively related to the weld size; the effect of weld size was less decisive in the Mela-Heinisuo calculation method.

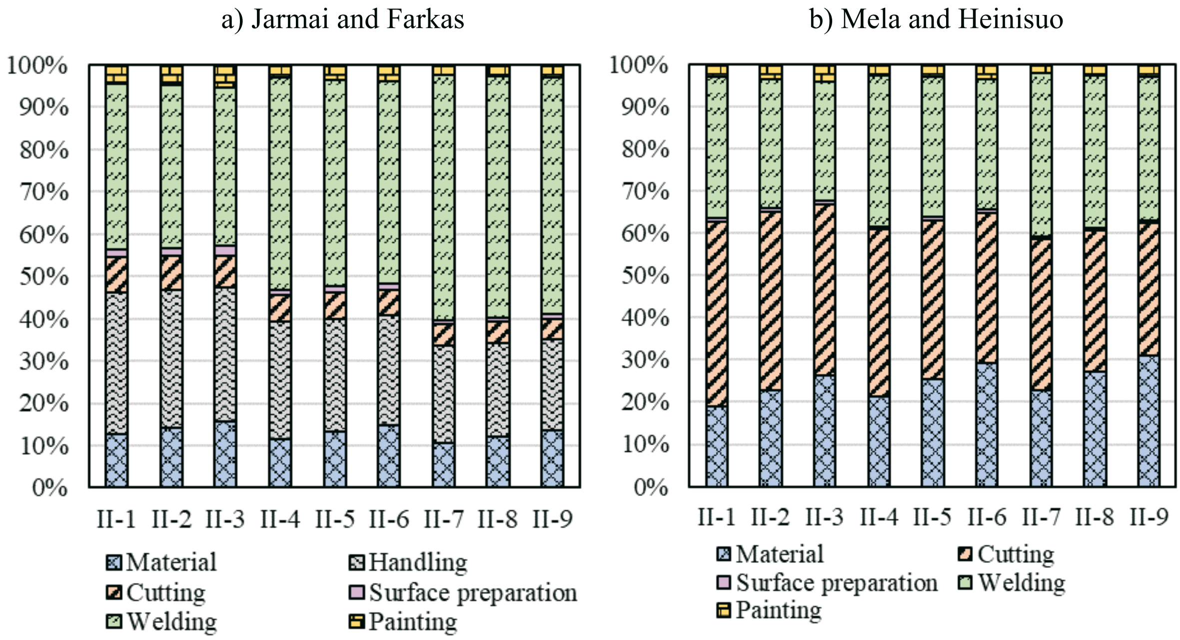

Fig. 4 Shares of partial fabrication and material costs in the total cost for the gearbox housing segment

Finally, surface preparation and painting costs were similar in both methods. Painting costs on average accounted for roughly 3% of the total cost, while the surface preparation costs were 1-2% in the Jarmai-Farkas method and less than 1% in that of Mela and Heinisuo.

When comparing the cost calculation methods in both selected cases, the Jarmai-Farkas method generally predicts that welding costs will take a larger share in the total costs than that in the Mela-Heinisuo method of. On the other hand, cost calculation done by the Mela-Heinisuo method yielded larger shares of cutting and material costs in both investigated cases. Finally, surface preparation and painting costs calculated by the two methods were similar.

5. Conclusion

Two methods used for calculating the costs of welded structures are compared in this paper. The aim was to determine whether their outputs will be consistent when the outer dimensions, plate thicknesses, and weld sizes are changed. Two cases were used to compare the two methods: a welded I beam and a gearbox housing segment. The welded I beam represents a classic case for which the calculation methods were initially developed. The gearbox housing segment has a more complex geometry and is more labour-intensive per unit of weight. As such, it was used to determine whether the outputs will remain consistent.

The results have shown that both methods provide rather similar total cost values as outputs. The greatest difference between the outputs was 14% for the welded I beam and 15.6% for the gearbox housing segment. On the other hand, the methods were not consistent when only partial fabrication costs were observed. As stated earlier, the Jarmai-Farkas method generally yielded higher welding costs, while the Mela-Heinisuo method predicted higher cutting and material costs. When considering the surface preparation and painting costs, both methods were consistent in both cases – the welded I beam and the gearbox housing segment.

Finally, based on the results, it can be concluded that the methods are consistent when considering the total cost values, despite significant variations in partial fabrication costs. By using the cost output values as a criterion for sorting the design variations, both methods provided similar rankings for the welded I beam. When considering the gearbox housing segment, several inconsistencies in the methods were observed.

6. Appendix

Table 2 Constants used in cost calculations

Method 1 – Jarmai and Farkas		**I**	**II**	**Method 2 – Mela and Heinisuo**		**I**	**II**
Preparation constant	C_1	1		Cost factor of the steel grade	K_M	1	
Preparation difficulty factor	Θ_d	2	2.5	Non-productive cutting time	T_{NCu}	3	
Number of parts	κ	3	15	Energy cost (cutting)	c_{EnCu}	0	
Welding constant	C_2	0.7899e-3		Energy cost (welding)	c_{EnBW}	0.08	
Welding size exponent	n_w	2		Cost of consumables (welding)	c_{CBW}	1.36	
Cutting constant	C_7	1.1388		Non-productive welding time	T_{NBW}	6.25	
Cutting exponent	n_c	0.25					
Surface preparation difficulty factor	Θ_{ds}	2					
Painting difficulty factor	Θ_{dp}	2					

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Submitted: 03.02.2022

Accepted: 20.4.2022

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