Cost sensitivity modelling in welding production

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ABSTRACT
The aim of cost sensitivity modelling (CSM) is to analyse the relevance of input data in weld cost or production investment calculations, and to show through iterative calculations how the final result is influenced by variations in input data. Today's welding production systems are complex installations both in terms of the technology used, day-to-day operation, maintenance and investment. This is evident with processes such as tandem-MAG and laser-hybrid MAG welding. The profitability of investment has been more in focus in recent decades than, for instance, production cost per m weld length or produced unit. CSM can be applied in traditional weld cost calculations (cost/m produced weld), and in complex investment calculations. Both cases are analysed in this paper to demonstrate the usefulness of the method. Two crucial questions arise as a consequence of CSM: what is the accuracy in the input data used, and which cost factor(s) are of prime importance? It is shown, for example, that deposition rate is not the only important cost-determining factor in sophisticated welding systems. CSM identifies other factors that must be controlled in order to keep deviations in profitability from target values within acceptable limits. The implementation time of a new investment is one such factor.

Keywords: welding production, weld cost, investments, sensitivity, risks

1. INTRODUCTION
Traditional weld cost and investment calculations have one common disadvantage. They both give the impression of being very accurate, which unfortunately is not the case in reality, and they can be misleading in decision-making situations. Used input data can be based on loose assumptions, rough estimates or (in the worst case) on pure guesswork. Often input data are not questioned, and performance values are not critically tested.

Optimisation of welding processes, choice of different welding methods (from a production economic point of view), the development and introduction of new welding methods, improvement of existing technology, and cost and investment calculations are all important issues in modern welding production. But today's welding engineers (such as IWE, International Welding Engineers) receive only a limited traditional education when it comes to weld cost calculations and are hardly trained at all in investment calculations. Normally "cost" is seen by welding engineers as cost per meter weld produced [1].

New welding technology and process inventions have always fascinated welding engineers and technicians. Although the traditional 'heavy' welding industry is declining in Western Europe and moving to the "East", several "new" welding methods have been introduced. These include friction-stir welding (FSW), tandem-MAG welding (double wire MAG welding) and laser-hybrid MAG welding (a combination of laser and MAG welding). Laser welding has made a clear breakthrough on the market and is today a well-established process.

Several of the new welding methods can increase productivity substantially compared with conventional installations. Productivity is often defined by welding engineers as welding speed for a certain weldment. Furthermore, new process solutions can also solve different design problems. Structures that previously could not be welded together are now joined in an economically efficient manner. For designers, process inventions have opened up new possibilities. Although the "new methods" can provide significant productivity gains, they have difficulties breaking through onto the market on a broad front.

Introduction of new welding technology can be justified in a business if it adds value to the operations (if is it profitable). The ultimate company goal should be that the new processes deliver increased profitability (return on investments) to a company or a project [2]. This is normally not obvious for welding engineers, partly because they are more involved in solving production or technical problems and only occasionally devote time to standard cost calculations (such as €/m weld produced), or because they evaluate the magnitude of different costs. Very seldom are they involved in
investment calculations. This is an area that is often analysed by economists [1-2], although several items in such calculations must be evaluated also by engineers, since technical benefits (so called 'added value') must be "dressed up" in economic terms. For instance: what is the value of decreased welding deformations (distortions) or higher process robustness? Therefore, in a more general case investment (and research projects) into the area that can be called new welding technology must consider two important concepts: productivity and efficiency.

As mentioned earlier, productivity in welding is measured as welding speed (travel speed) in a given case. Another measure is deposition rate, which is the deposited weld metal (produced) per unit time (kg/h). It is lower than the weight of electrodes and wires used, since there are also some losses during the welding operation. For a robot welding cell productivity can be measured by cycle time, arc time factor (equipment utilization factor), programming time, etc.

Efficiency, on the other hand, should be viewed in value terms. Basically it can be related to the question: "What customer problem is solved and what is the value of this solution?" New welding technology can solve several technical problems. For instance, it may mean better and more even quality, lower rejection rates, lower welding deformations and distortions, increased process robustness, more sustainable production, easier and faster assembly, new design solutions, better working environment for the operators, lower environmental impact, etc. In all cases, these benefits must be evaluated in economic terms; otherwise they have no economical meaning.

Both aspects must be considered. In the productivity case, this is normally done by carrying out traditional cost calculations, and in the efficiency case mainly through investment calculations [1].

From a production point of view the following issues are important.

- High throughput
- Stability in the process (robustness)
- No bottlenecks
- No reclamations or reworks.

In the future, a welding engineer will have to justify with economic arguments and analysis why a company should invest in new welding technology. This means that different cost and/or investment analyses will be used much more than today, and that the welding engineer will have to develop a certain skill in these areas.

In the welding industry there are many reasons for cost and/or investment calculations. They vary also between different industrial sectors, but are often due to the current situation (a certain customer problem calls for a solution) in a particular company. The following reasons, for example, can be mentioned with respect to traditional cost calculations:

- A current welding station is a bottleneck and it's necessary to investment in new equipment.
- The cost of a certain object must be lowered, and the parameters with highest impact on the cost are sought.
- The company is planning a transition from manual to robotic welding.
- The company must provide a quotation for a particular object.
- A new design has come into the manufacturing flow.

Investment calculations are certainly necessary when it comes to the more advanced welding technologies. Figure 1 shows schematically the relationship between capital (investment) cost and welding speed.

![Capital cost as a function of welding speed](image-url)

This article presents briefly the concept of sensitivity calculation in the welding industry. The basic welding cost calculation (€/m weld produced) is presented and discussed in sensitivity terms. This useful in the practical work of optimising welding procedure and gives a firm guidance in the most important cost-determining parameters. A modern high-capital investment object in the form of a laser-hybrid MAG welding station is then analysed.

2. COST SENSITIVITY MODELLING (CSM)

Cost sensitivity analysis can provide a meaningful tool for handling uncertainty (risks), and it can give guidance and direction for future work, for instance when optimising a certain welding procedure [1,4]. The analysis can be used to compare different alternatives and the impact of different assumptions under varying (input) conditions.
Optimization work, cost calculations and investment analyses, and the decisions based on them, never take place under certainty, but under conditions characterised by uncertainty and risk. It is, therefore, necessary to define and locate the specific decision-making problem in its real context, and to outline appropriate solutions considering uncertainty [4,5].

In a cost sensitivity analysis one examines whether the calculation results and conclusions are sensitive to changes in the original assumptions. Otherwise, the cost analysis presented may give the impression of being very accurate. In fact, the input data used may be based on loose assumptions and rough estimates. Normally one tends to forget to question the assumptions that lie behind different numbers, or critically examine input data [4].

Thus, the sensitivity analysis will estimate the uncertainty in the assumptions made (and will question them), and show by calculation how the uncertainty is influenced by different options. It provides a valuable guide to what's important and what can be ignored. Thus, one can rank the different cost factors, and focus further work on those that are most important from a cost or profit point of view. The analysis will thus provide the welding engineer with a better focus in certain projects.

Questions that normally arise in this context are, for example:

- Do we know all significant cost factors?
- Is the accuracy of the input data known?
- What cost factor or cost factors should you first concentrate on?

Sensitivity calculations can be made both for cost estimates, and for investment calculations. In the following, the idea of a sensitivity analysis is carried out for these two cases.

3. BASIC COST SENSITIVITY MODEL

The ordinary cost model in welding calculates the cost per m weld produced (or per welded object). Calculations are simple and straightforward, and are described in several standard textbooks [1], and it is therefore not necessary to repeat this information here. Instead, the input parameters used in the calculations will be reviewed briefly and the sensitivity implications of the basic cost model will be defined.

Input parameters in the cost calculations are:

- \( m_w \), weld metal weight (kg/m)
- \( TL \), cost for the welder including overhead (€/h)
- \( I \), deposition rate (kg/h)
- \( B_t \), arc time (utilisation) factor (%)
- \( MTK \), hourly (capital) machine cost (€/h)
- \( P_e, P_g \), prices for electrodes and shielding gas
- \( P_e, M_e \), costs for electricity and maintenance.

It can be shown that the total weld cost \( k \) (€/m) is given by the following equation.

\[
k = m_w \cdot (TL + MTK)/(I \cdot B_t)
\]

The assumption made in order to derive Eqn. 1 is that the costs for filler materials (wire + gas), electricity and maintenance have no large influence on the total welding cost. This is a valid assumption in many cases, because the sum of these costs is often < 10% of the total weld cost [1]. Eqn. 1 shows facts well-known to all welding engineers — that in order to decrease welding cost one has to reduce weld metal weight, and increase deposition rate and arc time factor.

It should be noted that the arc time (utilisation) factor \( B_t \) (defined as welding time/cycle time) is generally not the best measure of productivity. Increased welding speed will reduce the welding time, and, if the other operational times in a robot cell remain the same during one cycle, the arc time factor will be reduced, even though the throughput in the cell (number of items produced) will increase. This will be shown later with a practical example.

The sensitivity of \( k \) will now be analysed in two practical cases with the aid of Eqn. 1. The first one is a semi-automatic MAG (manual) welding of a fillet weld with a throat thickness of 4 mm. The second one is tandem-MAG welding (robot installation) of the same object (12 mm thick base material, ordinary C-Mn steel, SG2 wire and welding position PA). Table 1 gives the input parameters and the results for the two cases. These can be considered to be examples of the low-investment and the high-investment case, respectively.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Manual MAG</th>
<th>Tandem MAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_w )</td>
<td>0.13 kg/m</td>
<td>0.13 kg/m</td>
</tr>
<tr>
<td>( TL )</td>
<td>40 €/h</td>
<td>40 €/h</td>
</tr>
<tr>
<td>( MTK )</td>
<td>10 €/h</td>
<td>100 €/h</td>
</tr>
<tr>
<td>( I )</td>
<td>4 kg/h</td>
<td>12 kg/h</td>
</tr>
<tr>
<td>( B_t )</td>
<td>20 %</td>
<td>60 %</td>
</tr>
<tr>
<td>( k )</td>
<td>8.1 €/m</td>
<td>2.5 €/m</td>
</tr>
</tbody>
</table>

Input parameters for the two cases are average values for Swedish industrial welding. In the present calculation, costs for wire, gas, electricity and maintenance were, of course, omitted. These costs are normally strongly company-specific. A more thorough calculation showed, however, that these costs were below 7% of the total cost. Finally, the cost reduction is about 47% when converting from manual MAG to tandem-MAG (robotic) welding. This is mainly due to an
In the following sensitivity analysis, the input parameters were varied by ±10% from their original values in the two cases. These calculations clearly showed that weld metal weight and deposition rate are of prime importance for the weld cost in both cases. In the manual case, however, labour cost will be the dominant part and the machine cost has little impact. This contrasts with robot welding, where the machine cost is the major part of the total cost.

If the labour cost is the dominant part (manual welding), efforts should be made to reduce the welding time (arc time). This can be done in various ways, such as using higher deposition rates, working in the “best welding position”, redesign of the joint (reduced weld metal weight), etc.

If the investment costs are high (robot welding), it is essential to use the invested capital as efficiently as possible. Efforts should be made to reduce the cycle time and increase the arc time factor, which means better use of invested capital.

Consider now the influence of deposition rate \( I \), which is of great interest in both cases. This factor is crucial for all new welding techniques and the magnitude of it is often used a selling argument for new installations (such as tandem-MAG, which uses two wires).

As seen from Eqn. 1, \( k \) is sensitive to variations in deposition rate, weld metal weight, operator + machine cost, and arc time factor. A further analysis can be made in the following manner. First we take the derivate of \( k \) with respect to \( I \) and then with respect to \( MTK \). The results can be found in Eqns. (2) and (3).

Eqn. 2 shows that the weld cost \( k \) is more sensitive to variations in deposition rate (twice) than it is to variations in, for example, weld metal weight and arc time factor.

\[
dk / dI = -m_w \cdot (TL + MTK) / (I^2 \cdot B_f) \tag{2}
\]

If we on the other hand make the same reasoning for the high-investment case, the machine cost is of prime interest. Different companies have different ways to calculate the machine cost for their investments, and models such as net present value, internal rate of return, pay-back period, etc. are used, depending on the size of the investment.

With the same reasoning as before (differentiating \( k \) with respect to \( MTK \)), Eqn. (3) shows that the influence of the machine cost can be lowered by reducing the weld metal weight, and increasing deposition rate and arc time factor. Thus, in a high-investment case it becomes important to reduce the weld metal weight, through, for example, redesigning the weldment. Furthermore, the so-called “non-value adding times” during the welding cycle should be kept as low as possible (see also Eqn. 4). The design of the whole welding cell also becomes important, and it is essential to keep the “non-value adding times” as low as possible through efficient loading and un-loading procedures.

\[
dk / dMTK = m_w / (I \cdot B_f) \tag{3}
\]

The basic purpose of these calculations is not only to obtain insight into the impact of different parameters on the weld cost, but also to understand the impact of changes on the weld cost, and the validity of the calculations. Furthermore, we can outline and define steps and actions for different optimization activities (such as cost reductions).

One parameter that is crucial for the weld cost in both cases is the arc time factor \( B_f \). This is used extensively by welding engineers as a measure of the productivity, and the higher the value of \( B_f \) the better. However, this is not necessarily true in a practical situation. The opposite can in fact be equally valid if one considers throughput in a certain operation, and which will be shown with a real case.

But before that it is important to recognize the definition of arc time factor (or utilization factor).

\[
B_f = t_w / t_c \tag{4}
\]

where \( t_w \) is the welding time and \( t_c \) is the cycle time in, for example, a robot station. The cycle time is the sum of welding time + all other partial times connected with a certain job (loading, fixing, unclamping, cleaning, setting up, adjusting, stoppages, etc.) [1]. The welding time can be regarded as the only time that adds value to the product. This is, it must be admitted, a simplification, since some of the mentioned partial times have a supporting function. Table 2 shows the insufficiency of \( B_f \) as a productivity measure in welding operations.

<table>
<thead>
<tr>
<th></th>
<th>Case A</th>
<th>Case B</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_w )</td>
<td>20</td>
<td>10</td>
<td>-50%</td>
</tr>
<tr>
<td>( t_c )</td>
<td>60</td>
<td>50</td>
<td>-17%</td>
</tr>
<tr>
<td>( t_c - t_w )</td>
<td>40</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>( B_f )</td>
<td>33%</td>
<td>20%</td>
<td>-39%</td>
</tr>
<tr>
<td>Objects/day</td>
<td>420</td>
<td>504</td>
<td>+20%</td>
</tr>
</tbody>
</table>

In this case the welding time was reduced by 50%, because the welding speed could be doubled due to an innovative parameter setting (higher deposition rate). The weld metal weight was the same in the two cases. As can be seen from Table 2, the arc time factor (utilisation factor) is actually decreased by 39%, but the throughput in the robot station increases by 20%. The same result could, of course, be obtained by reducing the “non-value adding time”, \( t_c - t_w \). In any case, the capital used is better employed.

The basic cost model (Eqn. 1) also shows the dilemma with this equation if it is going to be used for modern
high cost/high productivity welding systems such as tandem-MAG welding. These systems can increase productivity (measured as deposition rate or welding speed) quite substantially. On the other hand, there is a considerable capital cost attached to the productivity increase.

This problem can be illustrated with the following example, where the weld cost has been calculated for five different cases, Table 3.

Table 3: Weld cost k according to Eqn. 1

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_w$</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>$TL$</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>$MTK$</td>
<td>10</td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>$I$</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>$B_i$</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>$k$</td>
<td>8.1</td>
<td>4.3</td>
<td>3.3</td>
<td>2.6</td>
<td>2.5</td>
</tr>
</tbody>
</table>

The results from Table 3 are given in Figure 2 as a function of hourly machine cost. It can be seen that the effect of investing in higher deposition rate is high when the machine cost is reasonably low. At high values of machine cost, in contrast, the effect is poor since k levels out and tends to a certain limiting value. Further investment into higher productivity (higher deposition rate with corresponding increase in machine cost) becomes more difficult to justify with the aid of Eqn. 1.

Fig. 2: Calculated weld cost as a function of hourly machine cost, according to Table 3.

4. INVESTMENT SENSITIVITY MODEL

It is appropriate to use the simple cost model dealt with earlier in situations where the cost per m weld is of main interest. It is less useful in high-capital investment cases, where the interest is focused on other (added) values that can be the outcome of the investment. These values may be, for instance, less rework and fewer reclamations, smaller welding deformations, easier assembly later in the production chain, the possibility of a new design, etc.

Large capital investment (greater than 0.5 – 1 M€) in the welding industry may take place under uncertainty and risk. Modelling and sensitivity calculations can then be used to sort out the main parameters that should be controlled in order to minimize the risk.

Risk can be defined as a combination of random, or insecure, events that may have a negative impact on certain key parameters of interest. The parameter of interest here is the profitability of a certain investment.

Evaluation of investment projects can be performed by using different models. Some of the best known models used in decision investment situations are [6]:

- Break-even analysis
- Sensitivity analysis
- Scenario method
- Theory of games.

In the remaining part of this section we will concentrate on sensitivity analysis. Sensitivity analysis will be understood as a certain calculation procedure used for predicting the effect of changes in input data on the output results of a model. In other words, sensitivity analysis can be described as a procedure that analyses how changes in certain input parameters (initial investment cost, implementation cost, implementation time, income per produced item, discounts, etc.) influence the profitability of a certain project [6].

Variations in input data can be due to several reasons, and uncertainty is probably one of the most important. Applying this in an analysis, it is possible to sort out the important parameters that influence profitability (by giving, for example, maximum and minimum values), and to conclude whether the investment project is justified or not.

Investment projects can be analysed with several methods (such as net present value, internal rate of return, pay-back period and annuities) for a given set input values. In the present case, the internal rate of return (IRR) method was selected, and the interest rate r was selected as the evaluation parameter, in contrast with the normal procedure (where the net present value is set to zero, and the corresponding interest rate is calculated). Calculations were made according to the following equation.

\[ I(0) = \sum_{i=0}^{n} b_i/(1+r)^i + V(n)/(1+r)^n \]  

where:

- $I(0)$ is the net investment made in Year 0
- $b_i$ is the net cash flow during Year $i$
- $n$ is the number of years
- $V(n)$ is the residual value in Year n.

The sensitivity of an investment into a laser-hybrid MAG welding station was then analysed using Eqn. (5). The equipment is shown in Figure 3.
This type of equipment is probably the most advanced type of equipment one could find in a welding workshop today. The total investment is about 1.00 M€. There are start-up costs during the implementation phase in Year 0 (for a pilot project, training operators, and implementation in the workshop). The start-up costs were estimated to be 0.06 M€. It was also assumed that the time for the implementation project was 6 months.

Operational costs arise during operation (for operators, electricity, gas, welding wire, maintenance, etc.). These were estimated to be 0.29 M€/year for a two-shift operation.

Income for the station is dependent on price per produced unit, volume, rationalisation effects, etc. The income was estimated to be 0.67 M€/year when the station was in full operation. A refurbishment was assumed to take place in Year 5 at a cost of 0.10 M€.

All these data were used in a spreadsheet IRR cash flow model, and the calculation was made with a +10% cost increase for investments, implementation and operation. Furthermore, a 10% lower price per produced unit was assumed, and 10% shorter cycle time in the robot cell. The influence of a 3-month delay in the implementation project and an increase from two-shift to three-shift operation were also included. The initial rate of return was 25% for the starting point. Results are shown in Figure 4.

A 10% cost increase during implementation has no influence on the IRR, whereas a similar increase in investment and operational costs lowers the IRR to 20%. An initial delay during the implementation (from 6 to 9 months) lowers the IRR to 18%. On the other hand, it is interesting to note the large influence of cycle time. If this is reduced by 10%, the IRR will increase to 37% (with a corresponding volume increase). A change from two-shift to three-shift operation gives an even greater increase in profitability (IRR = 51%).

5. CONCLUSIONS

The basic cost model presented in this paper is useful when calculating cost per m weld (or object) produced. It is sensitive to different engineering parameters. It was shown that the deposition rate (kg weld metal produced per unit time) exerts a powerful influence.

Labour costs dominate in manual welding, whereas the capital cost is of greater importance in robotic welding. Variations in deposition rate and arc time (utilisation) factor may have a negative impact on the production cost in capital-intensive systems.

Since an increased deposition rate is coupled to increased machine cost, the basic cost model cannot be used when justifying investment into capital-intensive systems. Other (added) values must be included that are not included in the basic model.

Investment sensitivity calculations indicate the major factors that are important when investing into high-capital systems. An internal rate of return model shows that the profitability of the investment is not sensitive to variations in start-up costs during the implementation phase.

However, delays during the implementation phase have a negative impact on profitability. A similar effect was seen when the operational (running) costs increased. On the other hand, optimisation work (aimed at reducing the cycle time) has a positive effect on profitability.

6. ACKNOWLEDGEMENTS

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7. REFERENCES


