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Sustainable welding process selection based on weight space partitions

Gunther Sproesser^{a,*}, Sebastian Schenker^{bc}, Andreas Pittner^d, Ralf Borndörfer^b, Michael Rethmeier^{ad}, Ya-Ju Chang^e, Matthias Finkbeiner^e

^aChair of Safety of Joined Components, Institute of Machine Tools and Factory Management, Technische Universität Berlin, Pascalstr. 8-9, 10587 Berlin, Germany

^bDepartment of Mathematical Optimization, Zuse Institute Berlin, Takustr. 7, 14195 Berlin, Germany

^cChair of Combinatorial Optimization and Graph algorithms, TU Berlin, Straße des 17. Juni 136, 10623 Berlin, Germany

^dGroup of Welding Technology, Department of Component Safety, Federal Institute for Materials Research and Testing, Unter den Eichen 87, 12205 Berlin, Germany

^eChair of Sustainable Engineering, Department of Environmental Technology, Technische Universität Berlin, Straße des 17. Juni 135, 10623 Berlin, Germany

* Corresponding author. Tel.: +49-30-8104-3893; fax: +49-30-8104-1557. E-mail address: gunther.sproesser@bam.de

Abstract

Selecting a welding process for a given application is crucial with respect to the sustainability of part manufacturing. Unfortunately, since welding processes are evaluated by a number of criteria, preferences for one or the other process can be contradictory. However, the prevalent procedure of weight assignment for each criterion is subjective and does not provide information about the entire solution space. From the perspective of a decision maker it is important to be able to assess the entire set of possible weightings and answer the question which welding process is optimal for which set of weights. This issue is investigated by means of a weight space partitioning approach. Two welding processes are considered with respect to three criteria that reflect their economic and environmental performance. In order to find the most sustainable welding process the underlying weight space partition is evaluated.

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1. Introduction

Welding is the most important joining technology and accounts for a large share of resource consumptions and manufacturing costs. Especially in the construction industry, metal plates above 10 mm thickness are joined using a vast amount of material and electricity [1, 2]. Generally, welding technologies differ in their economic performance and environmental impacts. Thus, choosing a technology for a given application is crucial for the welding costs and the environmental burdens [3-5].

In manufacturing, a clear preference for one technology cannot always be identified. Hence, a decision support system is needed that provides assistance in making a transparent and comprehensive judgement. One frequently applied approach is the weighted scoring method, also called value benefit analysis, that is described in basic engineering literature [6-8]. Alternatives are evaluated for multiple weighted criteria; the

alternative with the highest score is determined as the best one. For welding process selection, Rao [9] elaborated various methods such as Analytic Hierarchy Process, Compromise Ranking Method or Weighted Product Method. All presented multi-attribute decision methods include a decision table that comprises the criteria and the degree of fulfillment of each alternative. Despite their differences in calculating the score, all have subjective influences in common. Either just the assignment of weights or in addition the evaluation of a qualitative criterion are dependent on the assertive decision of the evaluator which could lead to misjudgments. Rao [9] suggested carrying out a sensitivity study for calculating the weights to assure the quality of the results. However this just covers a small part of the solution space and thus provides no thorough information about the influences of the weights.

So far, technologic and economic indicators have been the dominating criteria for process selection. As presented for example by Correia and Ferraresi [10] and Mirhedayatian et

al. [11], environmental or social issues are mostly neglected for the evaluation. On the other hand, Yeo and Neo [12] considered sustainability aspects by integration of a hazard scoring model into the process selection. This was extended to the broader scope of thin aluminum sheet joining by Chien et al. [13] who evaluated resistance spot welding, riveting and adhesive bonding with respect to costs, global warming potential and performance standards. In their publication, the multi-objective analysis of different weight settings highlights the importance of assessing the entire weight space. However, a comparison between different welding processes is not part of the publication.

In summary, subjective weight assignment of the current decision supporting methods can lead to disadvantageous choices. Furthermore, multi-objective analysis of welding technologies for thick metal plates including environmental performance indicators has not been intensively studied before.

Considering several possibly contradicting criteria a decision maker has to choose the welding technology that satisfies his or her needs best. A welding process A which is at least as good with respect to the given criteria as another welding process B and better for at least one criterion, dominates the welding process B. Hence, a decision maker is only interested in the feasible solutions that are non-dominated with respect to the given criteria. However, it might not be possible to find a solution that is preferable for any planned application scenario.

To address this challenge, this paper presents a method for welding process selection under consideration of multiple criteria. Each criterion is described by an affine function representing different life cycle stages. Moreover, the solution space regarding the process with the highest sustainable performance among others is assessed and identified by means of a weight space partitioning approach. In a case study for thick metal plate welding, two environmental criteria and one economic criterion are applied to model the performance of a manual and an automatic Gas Metal Arc Welding (GMAW) process. Finally, weight space partitions for three application scenarios are calculated and evaluated. The proposed method provides decision makers information about the entire solution space and thus helps to overcome the challenges of subjective weight assignment.

2. Methodology

2.1. Evaluation model

The score $S_c(p,l)$ of criterion c with respect to welding process p and weld seam length l will be given by an affine evaluation function in equation (1):

$$S_c(p,l) = m_{cp} \cdot l + n_{cp} \quad (1)$$

The intercept n_{cp} represents investments of life cycle stages of the considered welding process p with respect to criterion c that take place before the application of the process. The slope m_{cp} corresponds to variable shares with respect to a process p and a criterion c that depend on the use

phase of the technology. Referring to an economic cost criterion c , the intercept n_{cp} represents fixed shares of the costs such as purchase, installation and implementation of the equipment. The slope m_{pc} represents variable shares such as costs of labor or material. For an environmental criterion c , n_{cp} represents the corresponding impacts of sourcing and manufacturing of the welding equipment. The slope m_{cp} describes variable shares, for instance, greenhouse gas emissions that depend on the technology performance. The end of life phase of the equipment is assumed to have comparably minor importance based on findings of Junnila [14] and Schischke et al. [15] and is therefore neglected. The score value $S_c(p,l)$ with respect to criterion c and welding process p depends, furthermore, on the application scenario which is given by the overall weld seam length l that is planned to be joined with the considered process p . The score value is calculated from a perspective of a manufacturing company. See Fig. 1 for a depiction of an exemplified score function $S_c(p,l)$.

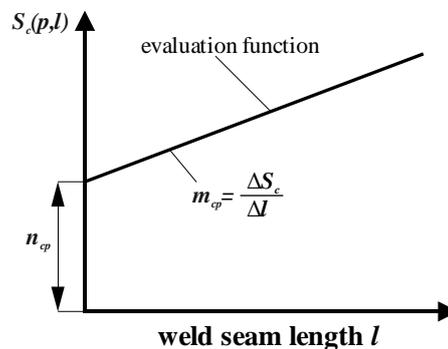


Fig. 1. Evaluation function

In order to create a dimensionless degree of fulfillment $DF_c(p,l)$ with respect to criterion c , process p and weld seam length l , the single scores $S_c(p,l)$ are transformed. Let $P = \{p_1, \dots, p_n\}$ be the set of considered welding processes and let C be the set of considered criteria. For a criterion $c \in C$ and a weld seam length l , define M_{cl} to be the minimum of $\{S_c(p_1,l), \dots, S_c(p_n,l)\}$. Then, the degree of fulfillment $DF_c(p,l)$ with respect to criterion c , process p and weld seam length l is defined to be the quotient $S_c(p,l) / M_{cl}$. Each degree of fulfillment can be considered dimensionless and assumes a value greater than or equal to 1. Consequently, an optimal process p for criterion c will assume a degree of fulfillment $DF_c(p,l)$ of 1 whereas a non-optimal process will assume a value greater than 1.

2.2. Multi-criteria decision support

The multi-criteria decision problem is modelled mathematically. Y_l is a set of points in \mathbb{R}^k where k is the number of considered criteria and l refers to the considered weld seam length l . Each point $y_p = (DF_{c_1}(p,l), \dots, DF_{c_k}(p,l))$ in Y_l consists of the degree of fulfillment values of welding process p for all considered criteria with respect to weld seam length l . Since all considered criteria are to be minimized, non-dominated points are defined as follows: A point $y \in Y_l$ is

non-dominated if there exists no point $z \in Y_i$ such that $z_i \leq y_i$ for $i = 1, \dots, k$ with a strict inequality for at least one $i \in \{1, \dots, k\}$. In order provide assistance to a decision maker, we consider for each point y_p in Y_i the set of non-negative weight vectors $w_p \in \mathbb{R}^k$ such that $w_p \cdot y_p \leq w_p \cdot y$ for all $y \in Y_i \setminus \{y_p\}$ where \cdot represents the dot product. If $w \cdot y_p \leq w \cdot y_q$ for welding processes p and q , then also $(xw) \cdot y_p \leq (xw) \cdot y_q$ for every scalar $x > 0$. Hence, no information is lost if the set of weight vectors is restricted to normalized vectors w , i.e., all $w = (w_1, \dots, w_k)$ with $w_i \geq 0$ and $w_1 + \dots + w_k = 1$. Let y_1 and y_2 be given points in Y_i . The weight space of y_1 is then given by equation (2):

$$w \cdot y_1 \leq w \cdot y_2, \quad (2)$$

$$\sum_{i=1}^k w_i = 1,$$

$$w_i \geq 0 \text{ for } i=1, \dots, k.$$

This set, given by a finite number of inequalities, is a polytope and consists of the positive weights for which y_1 is at least as good as y_2 . The weight space polytope for y_2 is similarly given where the inequality sign \leq is changed to \geq . These sets can be visualized and provide decision support for assessing the proper welding process.

3. Case study

3.1. Welding technologies

Generally, GMAW is one of the most frequently applied welding processes [16]. This is because GMAW offers high productivity, flexibility and can be executed automated or manually. Manual GMAW (M-GMAW) is popular in the steel construction industry because it enables easy adjustment of the process to the local geometry by the welder. On the other hand, manual welding limits the welding speeds, process powers and deposition rates to the human capabilities. Furthermore, low feasible process powers and precision of humans, in contrast to a welding robot, require root gaps and large groove angles, resulting in higher welding times and resource consumption. In contrast, automatic GMAW (A-GMAW) with higher process powers yields higher deposition rates and welding speeds. Recently, manufacturers of welding power sources developed modern arc processes as presented early by Dzelnitzki [17], and later summarized by Lezzi and Costa [18]. One innovation is an highly concentrated spray arc that enables higher penetration depths and the reduction of groove angles for V and double-V grooves. Consequently, modern modified spray arcs lead to reduced welding times and resource consumption.

The present study evaluates an A-GMAW and an M-GMAW process. Due to the mentioned disadvantages of manual welding, the M-GMAW process applies a conventional arc with a low process power and higher resource consumption. The robot movement of the A-GMAW process enables operation with a higher process power and a modified spray arc. This permits reduced flange angles and thus less resource consumption.

3.2. Environmental assessment

The intercept n_{cp} of the environmental evaluation functions represent the environmental impact of the equipment, i.e., the welding power source. Environmental impacts of the welding power source were taken from Schischke et al. [15], who presented a Life Cycle Assessment (LCA) for an average GMAW power source in Europe. In their publication, the LCA considered consumption of materials and electricity for manufacturing of the equipment without transportation to the location of operation i.e. the welding factory. For A-GMAW, the environmental burdens of the welding robot have to be included additionally. This was done by conducting a LCA based on a standard industrial robot. For the slopes B of the environmental evaluation functions, LCAs were carried out. LCA was adopted based on the current ISO standards [19, 20].

For the slopes m_{cp} , the goal was to apply LCA on M-GMAW and A-GMAW for a thick metal plate joint in order to calculate the environmental impacts of the use phase i.e. carrying out the welding processes. The scope aims at the welding processes themselves including the consumption of electricity, materials, and gases. The environmental impacts of the consumables are considered from a cradle-to-gate perspective. This means, e.g., the resource extraction and material processing of steel and gases, are included in the LCA. The functional unit is 1 m weld seam of a 20 mm thick metal plate. According to the scope definition and the functional unit, the inventory data of the inputs and outputs of the chosen welding processes were collected. Considered process inputs and outputs are filler material, shielding gas, electrical energy, and welding fumes. Data of the electricity, filler material and shielding gas consumptions were determined experimentally. Wall-plug efficiency of the GMAW power sources was set to 80 % according to latest measurements of Haelsig who used similar equipment [21]. Chemical compositions of consumed materials were taken from available product data sheets. Fume emissions are calculated according to emission rates of representative processes (power range and transfer mode) from the reference literature [22]. For A-GMAW, electric energy for robot movements was measured at the feed cable for the respective trajectories and added to the electricity consumption of the welding source in order to receive the overall electricity consumption. The inventory results and the technical parameters of A-GMAW and M-GMAW are shown in Table 1.

Table 1. Welding process parameters and process inventory

	M-GMAW	A-GMAW
<u>Basic Data</u>		
Groove preparation	Double-V (ISO 9692-1) 60° groove angle 1.5 mm root gap no root face	Double-V (ISO 9692-1) 30° groove angle 0.2 mm root gap 2 mm root face
Base material	Structural steel S960 Q (DIN EN 10025-6), 20 mm thick	Structural steel S960 Q (DIN EN 10025-6), 20 mm thick
Filler wire material	Matching wire	Matching wire
Type of shielding gas	82% Argon, 18% CO ₂	82% Argon, 18% CO ₂
<u>Process parameters</u>		
Average welding speed (cm/min)	37	40
Number of passes	6	2
Average power (kW)	8	12
<u>Input and output for LCA model</u>		
Filler material consumption (g)	1,200	530
Shielding gas consumption (l)	241	100
Energy consumption (kWh)	2.6	1.3
Welding fume emission (g)	6	1.2

The environmental impacts of the welding robot of the A-GMAW process considered the consumption of materials and electricity for robot manufacturing. According to the LCA of the welding power source, transportation of the robot to the location of operation was neglected as well. The inventory table based on the simplified bill of materials is shown in Table 2 and was taken from [23].

Table 2. Simplified bill of materials for the welding robot, adopted from [23]

	Amount in kg
Aluminum	219
Copper	250
Electronics	20
Plastics	85
Stainless Steel	63
Structural Steel	828

The CML 2001 method is adopted as the life cycle impact assessment method (as the midpoint approach). Meanwhile, GaBi 6.0 [24] was used as the software to carry out the LCA model. Considering the robustness, practicality, and the close relation between welding technologies and the metal related industry, the impact categories global warming potential with respect to 100 years (GWP) and eutrophication potential (EP) were selected for process evaluation.

3.3. Cost analysis

The cost evaluation function determines the total costs of welding considering the initial equipment costs and the costs

of operation. In the case study, the intercept n_{cp} equals the purchase price of the equipment, i.e., the price of a GMAW power source. For A-GMAW, investment for the welding robot has to be added. Exemplary prices were provided by a welding equipment manufacturer.

The slope m_{cp} consists of costs for labor, filler material, electricity and shielding gas. All operational costs were calculated based on the welding time per m weld seam length and the respective consumption rates. Average costs for labor considered German industrial workers based on data from the federal statistics office of 2013 [25]. The electricity price was set for a medium sized company in Germany according to the Eurostat database [26]. Shielding gas and filler material prices were provided by suppliers.

3.4. Evaluation

The intercepts n_{cp} and the slopes m_{cp} for the environmental and economic evaluation functions, respectively, are listed in Table 3 for M-GMAW and Table 4 for A-GMAW.

Table 3. Results of the LCA and cost analysis for M-GMAW

	n_{cp}	m_{cp}
EP in PO ₄ equivalent	$3.3 \cdot 10^{-2}$ kg	$7.5 \cdot 10^{-4}$ kg m ⁻¹
Costs	20,000 €	13 €m ⁻¹
GWP in CO ₂ equivalent	1,260 kg	4 kg m ⁻¹

Table 4. Results of the LCA and cost analysis for A-GMAW

	n_{cp}	m_{cp}
EP in PO ₄ equivalent	11.77 kg	$3.8 \cdot 10^{-4}$ kg m ⁻¹
Costs	80,000 €	5.3 €m ⁻¹
GWP in CO ₂ equivalent	7,939 kg	2 kg m ⁻¹

As it appears from Table 3 and Table 4 the values of the intercepts n_{cp} of the A-GMAW process are higher for all criteria. It is obvious that due to the lower values of the slopes m_{cp} of A-GMAW, the affine evaluation functions $S_c(l)$ have a common intersection for each criterion. The intersection with respect to costs is at a weld seam length of 7,792 m. With respect to GWP it is at 3,340 m and with respect to EP it is at 31,722 m. It is not hard to see that for any weld seam length $l \leq 3,340$ m, every convex combination of the criteria values of M-GMAW will be less than or equal to the same convex combination of criteria values of A-GMAW. Hence, for any weld seam length $l \leq 3,340$ m M-GMAW is preferable to A-GMAW. Equivalently, for every weld seam length $l \geq 31,722$ m A-GMAW is preferable to M-GMAW. The non-obvious cases lie in between these two application cases. Since not all application scenarios between a planned weld seam length of 3,340 m and 31,722 m can be assessed, three scenarios are investigated considering the following weld seam lengths: $l_1 = 5,000$ m, $l_2 = 7,792$ m, and $l_3 = 20,000$ m. The first scenario considers a weld seam length between the first and second intersection, which will yield weight space partitions most likely favoring M-GMAW. The second

represents the scenario which coincides with the second intersection. The third scenario considers a weld seam length between the second and third intersection, which will most likely favor A-GMAW.

Since we can restrict the weight vectors to non-negative values with $w_1 + w_2 + w_3 = 1$, w_1 and w_2 , respectively, determine the value of $w_3 = 1 - w_1 - w_2$. Hence, for a weight $w = (w_1, w_2, w_3)$ and a criteria point $y = (DF_{c_1}, DF_{c_2}, DF_{c_3})$, the weighted sum is $w^T \cdot y = w_1 \cdot DF_{c_1} + w_2 \cdot DF_{c_2} + (1 - w_1 - w_2) \cdot DF_{c_3}$. The weight spaces can be depicted in 2-dimensional figures. All weight vectors $w = (w_1, w_2, 1 - w_1 - w_2)$ for which the point y_l^M of M-GMAW and weld seam length l yields a better value with respect to the weighted sum $w^T \cdot y_l^M$ than A-GMAW and $w^T \cdot y_l^A$, respectively, are contained in the green subset depicted in Fig. 2, Fig. 3 and Fig. 4. Similarly, all weight vectors $w = (w_1, w_2, 1 - w_1 - w_2)$ for which A-GMAW yields a better weighted sum value are contained in the blue subsets. For all weight vectors w being on the line intersecting both subsets it holds that $w^T \cdot y_l^M = w^T \cdot y_l^A$.

4. Results

The first scenario with a weld seam length $l = 5,000$ m is depicted in Fig. 2. The corresponding points $y = (DF_{EP}, DF_{costs}, DF_{GWP})$ are $y_{5,000}^A = (3.61, 1.25, 1)$ and $y_{5,000}^M = (1, 1, 1.19)$. The second scenario considers the weld seam length $l = 7,752$ and the corresponding weight space partition is depicted in Fig. 3. The corresponding degrees of fulfilment are $y_{7,792}^A = (2.5, 1, 1)$ and $y_{7,792}^M = (1, 1, 1.38)$. The third scenario with a weld seam length $l = 20,000$ yields the weight space in Fig. 4. The corresponding degrees of fulfilment are $y_{20,000}^A = (1.29, 1, 1)$ and $y_{20,000}^M = (1, 1.51, 1.7)$.

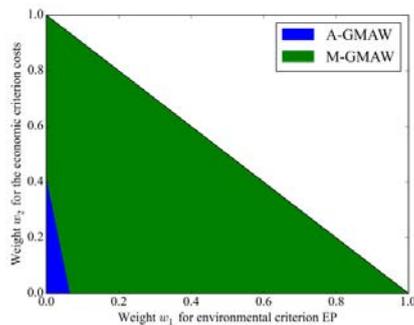


Fig. 2. Weight space partition for $l = 5,000$ m

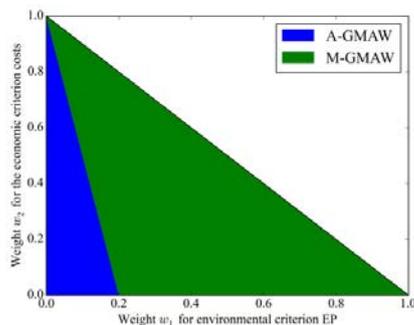


Fig. 3. Weight space partition for $l = 7,792$

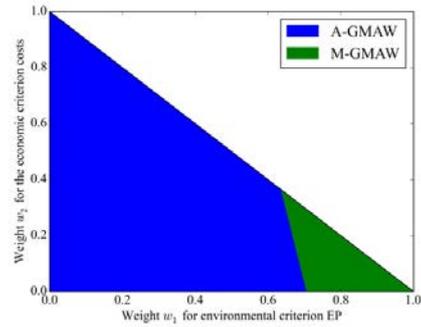


Fig. 4. Weight space partition for $l = 20,000$

5. Discussion

Results of the evaluation highlight the importance of considering multiple criteria and life cycle stages. In the evaluation model, the intercepts n_{cp} represented life cycle stages prior to the use phase. Results showed that especially the environmental impacts in the criterion EP (see Table 3 and Table 4) significantly differed which emphasizes the strong influence of the equipment on the sustainability of the process. Taking into account more than one environmental criteria, e.g. EP and GWP, leads to considerable effects on the evaluation model and thus on the decision. Therefore, the integration of all criteria relevant for the sustainability of a welding process is necessary in order make sustainable decisions.

Since there exist economies of scale favoring A-GMAW with increasing weld seam length in all criteria, it is obvious that the set of weight vectors for which A-GMAW is optimal with respect to the weighted sum grows from scenario 1 to scenario 3 and contains all possible weight vectors after 31,722 m. In an application case assuming six hours of welding per shift, two shifts per day and 200 working days for a workplace, the limit of 31,722 m would be reached after four years of M-GMAW.

It can be observed that the hyperplane dividing the green and blue subsets has a large negative slope in all three scenarios. As a result, there is a relatively narrow range of weights for EP in which the determination of the weight value for the criterion is not the decisive factor. Consequently, the preferred process is determined only by the importance or weight of the criterion EP. This derives from a relatively large gap between the evaluation values of the criterion EP and the other two criteria as well as from the linear nature of the evaluation functions. In the first scenario an eutrophication weight of at least 0.067 results in M-GMAW being preferable independent of the cost and GWP weight. This means that only between an EP weight value of 0 and 0.067 the choice of the cost weights w_2 and GWP weight w_3 , respectively has an impact and might lead to a change of the preferred welding process. An equivalent observation holds true for the second scenario with EP weight values between 0 and 0.2. In the third scenario an eutrophication weight of at least 0.7 yields M-GMAW to be preferable.

6. Conclusion

In this paper a methodology for sustainable welding process selection based on a weight space partitioning was presented. In a case study, two state-of-the-art welding processes, manual and automatic GMAW, were evaluated with respect to an economic criterion and two environmental criteria. For the environmental criteria, LCA's were conducted in order to reflect the environmental burdens. Total costs were determined by equipment prices and operational costs for labor, electricity and materials of the use phase. Results show a significant influence of the life cycle stages (investment, equipment manufacturing) prior to the use phase and the environmental criteria eutrophication. In contrast to prior work considering only a few weightings of the criteria, the presented methodology yields an holistic approach which provides a global perspective on the distributions of the weights. This helps to overcome the possible problem of selecting a less sustainable technology based on subjective weight assignments. The weight space partitions and their visualization enable a decision maker to assess the sensitivity of the selection problem and thus will come to a more confident decision.

A valuable property of the weight space approach is its independence of the number of considered criteria. In order to consider more complete sustainability aspects into the decision supporting model, relevant criteria including the social dimension could be added to the current set of criteria without any methodological restrictions. Due to the currently high discrepancy of the economic and different environmental evaluation values, single criteria have a dominant influence on the weight spaces. Therefore, it is important to monitor future technological changes that will affect single criteria and thus the multi-criteria evaluation.

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