Sustainable Technologies for Thick Metal Plate Welding

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Abstract Welding is the most important joining technology. In the steel construction industry, e.g. production of windmill sections, welding accounts for a main part of the manufacturing costs and resource consumption. Moreover, social issues attached to welding involve working in dangerous environments. This aspect has unfortunately been neglected so far, in light of a predominant focus on economics combined with a lack of suitable assessment methods. In this chapter, exemplary welding processes are presented that reduce the environmental and social impacts of thick metal plate welding. Social and environmental Life Cycle Assessments for a thick metal plate joint are conducted for the purpose of expressing and analysing the social and environmental impacts of welding. Furthermore, it is shown that state-of-the-art technologies like Gas Metal Arc Welding with modified spray arcs and Laser Arc-Hybrid Welding serve to increase social and environmental performance in contrast to common technologies, and therefore offer great potential for sustainable manufacturing.

Keywords Life Cycle Assessment (LCA) · Arc Welding · Laser Arc-Hybrid Welding · Resource efficiency · Social Life Cycle Assessment (SLCA) · Human health

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1 Introduction

Welding plays a pivotal and irreplaceable role in modern manufacturing. The applications are involved in nearly all industries, for example, construction, automobile, turbine production, etc. Yet welding processes require large amounts of energy and resources which are of course critical from an environmental perspective. Social aspects of welding meanwhile mainly involve health effects associated with welding fumes and welder compensation.

Common welding technologies include Gas Metal Arc Welding (GMAW), Manual Metal Arc Welding (MMAW) and Laser Arc-Hybrid Welding (LAHW), which all differ tremendously in their properties and potential in the realm of sustainable manufacturing.

MMAW with coated electrodes is a popular welding technology on building sites due to the fact that it offers high flexibility and requires no shielding gas supply. Additionally, low costs of equipment and electrodes incentivize the frequent application of MMAW. On the other hand, the productivity attached to MMAW tends to be low due to limited welding speeds, process power capacity limitations, as well as the attendant additional time consumption at play when changing the electrode and removing the slag. Furthermore, MMAW is performed manually, which entails significant health risks for welders.

Meanwhile GMAW is one of the most widely used technologies due to the fact that it is easy to automate and offers a high level of productivity and flexibility. The typical operation mode of GMAW for the purpose of achieving high deposition rates and process speeds, is automatic welding with spray arc transfer. Recently, manufacturers of welding power sources have developed modern arc processes as presented early by Dzelnitzki (2000), and later by Lezzi and Costa (2013). One innovation is a highly concentrated spray arc that enables higher penetration depths and the reduction of flange angles. Consequently, the modern modified spray arcs lead to reduced material consumption which prove to be promising with respect to environmental aspects.

Then there's LAHW, which remains a rather young technology compared to those mentioned above, yet is well on its way as a promising new field of sustainable manufacturing. In comparison with GMAW, LAHW achieves higher welding speeds and hence higher productivity, while the reduced number of passes and lower volume of molten material lead to resource savings, lower distortion and less rework. Yet when it comes to large structures with high geometrical tolerances of several millimetres, gap bridging can be a critical issue ultimately limiting the application of LAHW as it stands.

For manufacturing processes and products, environmental and social issues are often insufficiently considered and respected. The negative effects on the environment and humans however accumulate, many of which are also irreversible. To evaluate the environmental impacts and social influences of a process or product, Life Cycle Assessment (LCA) (ISO 2006a; Schau et al. 2012), and Social Life Cycle Assessment (SLCA) (UNEP 2009) are the current state-of-the-art methodologies. LCA is an ISO standardised method, widely employed for providing an estimate on the potential environmental impacts of products through the whole life cycle (Schau et al. 2012; Klöpffer and Grahl 2009; Guinée et al. 2002). It is the most advanced and tried-and-true methodology in evaluating environmental burden on process or product levels, and also in preventing burden shifting from different life cycle phases.

According to the guidelines for Social Life Cycle Assessment of Products (UNEP 2009), SLCA is defined as a methodology that aims at assessing the potential positive and negative social and socio-economic impacts related to human beings affected by products/services throughout the life cycle, such as health and wage issues of workers, etc. Though SLCA studies have increased in number significantly within the last three years, the method is still considered to be rather in its infancy (Neugebauer et al. 2015).

To date, welding technology developments and comparisons remain predominantly focused on economic indicators. Environmental and social aspects are insufficiently taken into account when evaluating and choosing a process for a given welding task. To that end, MMAW, LAHW and automatic GMAW with a conventional spray arc and a modified spray arc, have been evaluated in view of the environmental and social aspects attached. SLCA and LCA have been applied to compare the corresponding environmental impacts and the potential health risks to welders, particularly caused by welding fumes. Moreover, the wage status of welders in Germany has been investigated with a discussion of the fairness and adequacy given their working and living conditions. The results can help the industry to identify the crucial issues and then offer improvements to the processes and equipment in pursuit of more sustainable alternatives.

2 Methodology

2.1 Environmental Assessment

According to the ISO standard, the methodology is divided into these four phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation in an iterative process (ISO 2006a, b). First of all, the goals of this LCA study are to highlight the environmental impact contributed by different inputs and outputs of the chosen welding processes, and to compare the differences in environmental impact. The results are expected to provide information for welding process development and selection. The scope of the study is concerned with the welding processes in and of themselves, including the life cycle stages of material acquisition (involving in raw material extraction and processing of the used material in welding processes), the manufacturing phase (carrying out welding processes), and waste management. In line with the defined scope, the system boundary covers the consumption of electricity, materials and gases, and landfill

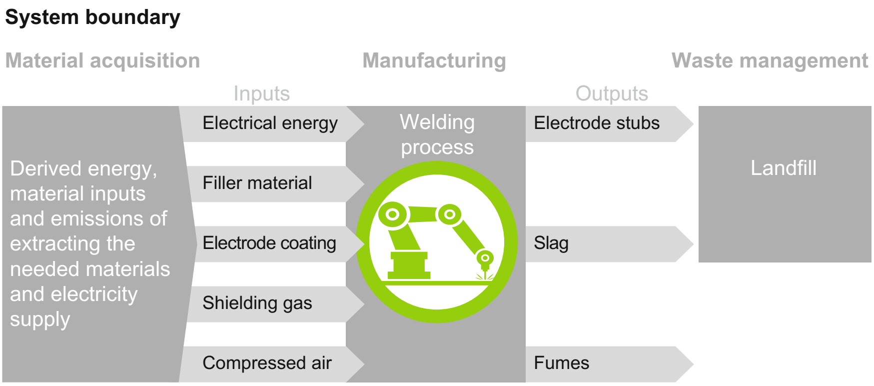

Fig. 1 System boundary and inputs and outputs of welding processes (Sproesser et al. 2015)

waste, but stops short of considering machinery. The functional unit is 1 m weld seam of a 20 mm thick metal plate. The input and output information based on the defined functional unit will be collected and calculated in life cycle inventory analysis stage. In this study, the CML 2002 method is adopted as the life cycle impact assessment method (as the midpoint approach). Meanwhile, GaBi 6.0 (by thinkstep) is used as the software to build and carry out the LCA model.

In the life cycle inventory analysis phase, the inventory data of inputs and outputs of the chosen welding processes are collected according to the system boundary and the functional unit. Figure 1 shows the considered process inputs and outputs, filler material, shielding gas, electrical energy, welding fumes, compressed air (for LAHW), electrode coating (for MMAW), electrode stubs (for MMAW), and slag (for MMAW).

Electricity consumption for the welding processes was determined with values measured and the respective wall-plug efficiency of the equipment. The wall-plug efficiency of arc welding machines (MMAW, GMAW and the arc content of LAHW) was set to 80 % (Sproesser et al. 2016; Hälsig 2014). For LAHW, electricity consumption of the beam source took into account process power, an efficiency of 30 %, and additional contributions of the cooling unit. Electric energy for robot movement was measured at the feed cable for the respective trajectories and added to the electricity demand of the welding source in order to calculate the overall energy utilised for the joining process.

The consumption of filler material was determined by measurement of the wire feed rate and in the case of MMAW, by weighting the electrodes and by collecting the remaining electrode stubs. The chemical compositions of the materials were taken from available product data sheets. For MMAW, only titanium dioxide (45 %) and silicon dioxide (10 %) were considered to represent the main composition of the electrode coating due to missing data in the GaBi data base. The consumption of compressed air for LAHW was estimated by applying Bernoulli's principle to the geometry of the cross-jet unit of the laser head.

Table 1 Fume emission rates of the applied welding processes

	Emission rate
MMAW	4 mg/min (Pohlmann et al. 2013)
GMAW standard	6 mg/s (Rose et al. 2012)
GMAW modified	4 mg/s (Rose et al. 2012)
LAHW	LAHW root pass: 10.4 mg/s (Pohlmann et al. 2013) GMAW filler pass: 6 mg/s (Rose et al. 2012)

Fume emissions are calculated according to emission rates of representative processes (power range and transfer mode) from literature (Pohlmann et al. 2013; Rose et al. 2012) and are displayed in Table 1. The chemical composition is assumed to be mainly from iron oxide (Antonini et al. 2006; Jenkins and Eagar 2005).

Considering the robustness, practicality, and the close relationship between welding technologies and metal related industry, the four indicators: global warming potential (GWP), eutrophication potential (EP), acidification potential (AP) and photochemical ozone creation potential (POCP) have been selected for further comparison in life cycle impact assessment stage (World Steel Association 2011; PE International 2014). GWP (100 years, in kg of carbon dioxide equivalent) evaluates the long-term contribution of a substance to climate change. EP (in kg phosphate equivalent) estimates the impact from the macro-nutrients nitrogen and phosphorus in bio-available forms on aquatic and terrestrial ecosystems, affecting undesired biomass production. AP (in sulfur dioxide equivalent) addresses the impacts from acidification generated by the emission of airborne acidifying chemicals. Acidification refers literally to processes that increase the acidity of water and soil systems by hydrogen ion concentration (Institute for Environment and Sustainability of Joint Research Centre of European Commission 2010). Then there's POCP (in kg ethene equivalent), which rates the creation of ozone (due to reaction of a substance in presence of NO_x gases), also known as summer smog (Guinée et al. 2002). The negative impact causes respiratory diseases and oxidative damage on photosynthetic organelles in plants (Institute for Environment and Sustainability of Joint Research Centre of European Commission 2010). In the final phase, the results from life cycle impact assessments are interpreted.

2.2 *Social Assessment*

In the SLCA guidelines, the methodology framework is proposed similar to LCA: goal and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation (Chang et al. 2012; UNEP 2009). In the guidelines, five main stakeholder groups (workers, consumers, local community, society and value chain actors) and 31 subcategories are described and the relevant social issues are then listed. Due to the high level of importance held by the stakeholders responsible for welders' welfare in Germany, the two critical social conditions "fair salary" and "health and safety" have been selected for the social assessment.

The sufficiency status of salary for welders in Germany can be recognized by comparing the average wage of welders (FOCUS Online 2012), the national minimum wage (Statistisches Bundesamt 2016a) and at-risk-of-poverty threshold (Statistisches Bundesamt 2016b). The at-risk-of-poverty threshold serves as a yardstick for identifying whether people live in income-dependent poverty. In this chapter, gross monthly wage and poverty threshold for a single person are used for comparison. The reference year for the national minimum wage and at-risk-of-poverty threshold is 2015, but the average wage of welders is taken from 2011 due to the statistical data limitation.

In addition to fair salary, the relative health and safety effects on welders performing different welding technologies have been analysed, with a specific look at exposure to welding fumes. Welding processes generate a complex mixture of fumes (respirable and ultrafine particles) as by-products composed of an array of metals volatilised from the welding electrode or the flux materials incorporated (Antonini et al. 2006). Welders' exposure to welding fumes is often associated with acute and chronic lung damage, lung cancer and other potential harm on heart, kidneys and central nervous systems (Gonser and Hogan 2011; Canadian Centre for Occupational Health & Safety 2016). Iron oxides constitute the main part of the fume, while chromium, manganese, and nickel account for the total remaining fume composition (Antonini et al. 2006; Jenkins and Eagar 2005). Iron oxide is not officially classified as a human carcinogen. Nevertheless, it has proven to trigger siderosis, which decreases lung capacity. Chromium (VI, insoluble) and its compounds are known as a human lung carcinogen, while nickel is also known as a human carcinogen, causing lung, nasal, and sinus cancers. Manganese and its compounds are not carcinogens, but associated with central nervous system (CNS) effects similar in nature to Parkinsonism (Gonser and Hogan 2011). To represent the relative potential risk caused by fumes on the health of welders, we have identified the hazard figure (Gefährdungszahl, *GZ*) of the welding processes. Based on the literature (Spiegel-Ciobanu 2012), the model simplifies and considers process-specific fume emissions associated with the working situation. For estimating the simplified potential risk GZ_s, the following Eq. 1 is used (Spiegel-Ciobanu 2012):

$$GZ_s = \left(E_p \times W_p\right) \times L \times R \times K_b \tag{1}$$

E_p = emission factor of the specific substance per functional unit;
W_p = potential effect for the specific substances in fume;
L = ventilation factor (have sufficient ventilation or not);
R = spatial factor (outside or in rooms);
K_b = the factor of relative distance of head/body and fume source.

E_p represents the fume emissions per functional unit of 1 m weld seam and is calculated based on the inventory data for fume emissions of the LCA (see Sect. 2.1). It is a relative factor taking the minimal emissions per functional unit as a reference value. Since the distance between welders and fume sources in different welding processes vary widely, the K_b levels are set correspondingly. The closer distance indicates a higher chance of inhaling fume. MMAW is executed manually and welders are close to the fume sources, so the levels are set as 4 (Spiegel-Ciobanu 2012); in GMAW (executed with a robot), the K_b level is assumed as 2 due to there usually being some distance between welders and fume sources; in LAHW, the welding process is performed in welding cells, so the K_b level is defined as 1 (Spiegel-Ciobanu 2012). Targeting the comparison of potential risks, W_p can be assumed as the same value as 1 to represent no difference in comparison between the processes since the composition of materials in the chosen welding processes are highly similar. Also, the L and R both are set as 1 in the paper due to the condition of welding places assumed to be identical. Following Eq. 1 and the assumptions, the potential health risk, GZ_s, is highly influenced by the emission factor per functional unit E_p and the relative distance of head/body and fume source K_b. The GZ_s can be simply represented as $E_p \times K_b$.

2.3 Welding Experiments

Welding was carried out in four types of technologies: MMAW, LAHW, and GMAW in modified spray arc (GMAW modified) and the conventional spray arc (GMAW standard). Low alloyed structural steels and proper filler wires were used as a base and filler metal. Weld samples were plates of 20 mm thickness with weld seam lengths from 250 to 300 mm. Welding was performed in the flat position

Table 2 Material, joint specifications and process parameters of MMAW and LAHW

	MMAW	LAHW
Joint preparation	Double-V (ISO 9692-1) 60° groove angle 2 mm root gap 2 mm root face	Y-groove (ISO 9692-1) 45° groove angle No root gap 14 mm root face
Base material	S355 + N (DIN EN 10025-3)	X120 (API 5L)
Filler material	E 42 0 RR 1 2 (DIN EN ISO 2560-A)	Mn4Ni2CrMo (DIN EN ISO 16834)
Shielding gas	–	82 % Argon, 18 % CO_2
Process parameters		
Average welding speed in mm/s	2.8	LAHW: 43.3 GMAW filler pass: 13.3
Number of passes	8	2
Average power in kW	4	Root pass: 33 (Laser + GMAW) Filler pass: 11 (GMAW only)

Table 3 Material, joint specifications and process parameters of GMAW standard and GMAW modified

	GMAW standard	GMAW modified
Joint preparation	Double-V (ISO 9692-1), 60° groove angle 0.4 mm root gap 2 mm root face	Double-V (ISO 9692-1) 30° groove angle 0.2 mm root gap 2 mm root face
Base material	S690 QL (DIN EN 10025-6)	S960 QL (DIN EN 10025-6)
Filler material	Mn3Ni1CrMo (DIN EN ISO 16834)	Mn4Ni2CrMo (DIN EN ISO 16834)
Shielding gas	82 % Argon, 18 % CO_2	
Process parameters		
Average welding speed in mm/s	6.2	6.7
Number of passes	4	2
Average power in kW	8	12

(1 G) and data was calculated with regards to the functional unit of 1 m weld seam. Material specifications, groove preparations and process parameters of the processes are listed in Tables 2 and 3.

3 Case Study Results and Discussion

3.1 Environmental Assessment

The LCA study highlights the environmental impacts contributed by different inputs and outputs of the chosen welding processes and compares the differences of environmental impacts. The life cycle inventory data is shown in Table 4 based on the functional unit. The inventory is used to conduct life cycle impact assessments.

By carrying out impact assessment within CML method and GaBi 6.0 software, the environmental impacts GWP, EP, AP and POCP contributed by the selected welding processes have been estimated, as shown in Fig. 2. The results indicate that MMAW causes the highest environmental impact in the chosen impact categories among the selected processes, and the LAHW variant provides the lowest. In addition, the modified spray arc with the smaller groove angle contributes significantly lower impact than the standard GMAW variant. For GMAW and LAHW, electric energy and filler material are the dominant influencing factors. For MMAW, the electrode coating is of major relevance, along with filler material and electric energy.

Table 4 Life cycle inventory of the welding processes

	MMAW	GMAW standard	GMAW modified	LAHW
Filler material in g	944	890	530	155
Shielding gas in l	–	241	100	33
Electrode coating in g	580	–	–	–
Compressed air for laser optics cross-jet in l	–	–	–	249
Electric energy in kWh	3.9	2.1	1.3	0.9
Welding fumes in g	11.6	3.6	1.2	0.6
Slag in g	600	–	–	–
Electrode stubs in g	150	–	–	–

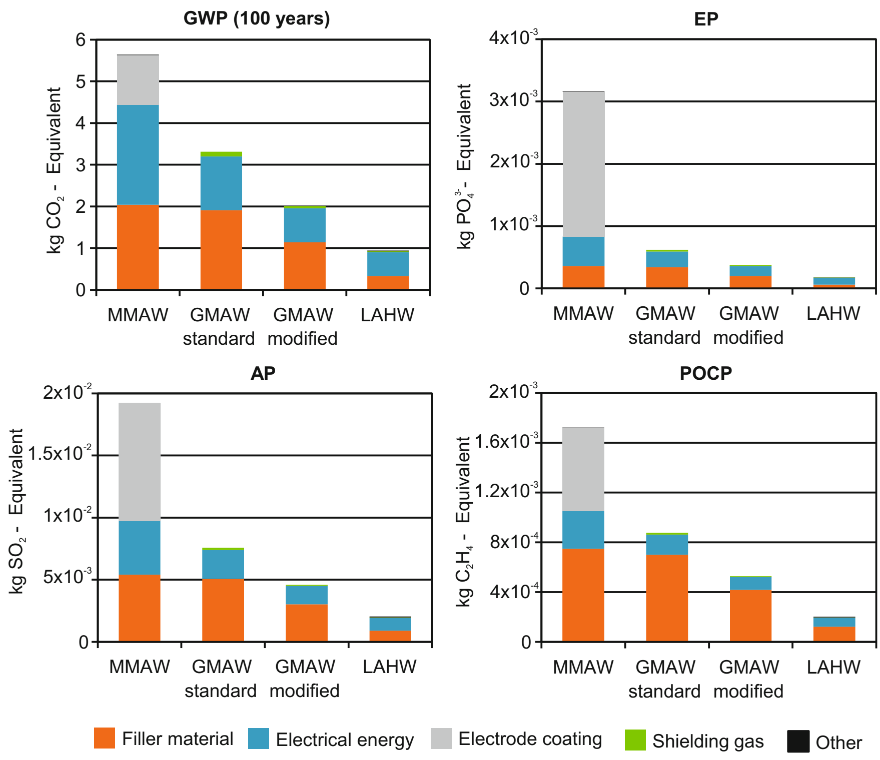

Fig. 2 Results of the impact assessment

Among the processes investigated in joining a 20 mm thick plate of structural steels, LAHW is the best option hands down when considering the environmental impact caused. Due to its high power density, LAHW performs welding with both the least number of passes and overall weld volume. Additionally, LAHW allows for high welding speed, leading to high productivity and low electricity and gas consumptions. This is a remarkable finding considering the low beam source efficiency of 30 % in contrast to 80 % efficiency of arc welding machines. The main reason for less environmental impact in LAHW lies in the better ratio between power consumed and welding time, which means that the low efficiency is overcompensated by welding time savings. Either filler material or electric energy is dominant depending on the indicator considered. Both can be optimized by means of enlargement of the root face width and a smaller opening angle. Moreover, electric energy consumption could be further reduced significantly by increasing the beam source efficiency.

Contrary to LAHW, low process performance (deposition rate and welding speed) and the necessary edge preparation in MMAW lead to the highest environmental effects. Low deposition rate and welding speed result in higher amounts of energy that are used to re-melt weld metal in the subsequent passes, as well as energy losses due to heat conduction into the base material. Furthermore, electrode coating accounts for a remarkable share of environmental impact even though only 55 % of the electrode composition is considered in the LCA model. It is likely that results would be even worse for MMAW if electrode coating could be fully accounted for. In order to mitigate environmental impact, the industry should therefore focus firstly on rutile electrode coatings and then on joint design. Smaller root gaps and opening angles would reduce electric energy and material (filler as well as coatings) consumption. Thickness of electrode coatings can be reduced and alternative compositions can be further investigated (e.g. basic or acid coated electrodes) with respect to their environmental impact.

Filler material consumption dominates about 54–80 % of the instances of impact in GMAW in the chosen categories. The benefit of reducing opening angles can be directly stated by comparing GMAW with the standard spray arc and the modified spray arc. This leads to approximately 40 % reduction of the environmental impact level. Hence, in order to improve GMAW from an environmental perspective, joints should always be designed with the minimum possible flange angle. However, it is unclear whether optimisation options are technologically feasible or whether they guarantee the optimal weld performance, all of which should be evaluated properly.

Welding robot movements for all technologies account for a small share of electricity consumption. As a result, the energy efficiency attached to joining industrial parts is dominated by the welding process itself and has to be adequately assessed in future work accordingly.

The LCA results show clear environmental preferences. Nevertheless, gaps and limitations of the study must be acknowledged, for example the challenges embedded in LCA methodology (Finkbeiner et al. 2014) and the possible variation of results due to different process requirements in welding technology. Process requirements such as efforts for edge preparation, effects of different welding positions or mobility of equipment could furthermore have a crucial influence on process selection. In the LCA model, only four impact categories are considered for comparison, which can lead to inconclusive judgment. What's more, machinery is not considered, which could cause potential bias and require a critical overall weld seam length before proving to be environmentally beneficial.

3.2 Social Assessment

The latest salary survey from Focus Online (FOCUS Online 2012) showed the average gross salary per month of welders in Germany in 2011 to be €2,165; the national minimum wage was €1,430 (Statistisches Bundesamt 2016a); and the poverty threshold for a single person was deduced to be €986.67 based on the national statistics (Statistisches Bundesamt 2016b). The results indicate that the average monthly wage of welders is higher than the current national minimum wage and the deduced poverty threshold (approximate 2 times). It is therefore fair to conclude that welders' salary status is sufficient for supporting their overall subsistence and for meeting the income regulation of minimum wage.

The evaluation of the potential risks GZ_s of the applied welding processes are displayed in Table 5. The emission factors E_p are calculated based on the inventory data shown in Table 4, taking the emission of LAHW as the reference value for estimating the ratios. Thus, LAHW constitutes the lowest potential health risk. This is because it is conducted in closed cells due to laser safety restrictions. MMAW owns the highest GZ_s to welders among all the selected processes. GMAW standard and GMAW modified have smaller differences of the GZ_s since they only differ in the quantity of fume formation. The results underline that welders working in the manual processes (like MMAW) face higher risks than in automatic processes (GMAW, LAHW). Consequently, it is important to limit the application of manual welding processes to the minimum possible extent. Moreover, the personal protective equipment used should be adequate to minimize the health risks for welders. In case of automatic GMAW, the future goal should be to keep welders out of the process zone. However, this requires technologies for advanced process control and monitoring to ensure the quality of the welds. Apart from the potential health risks posed by welding fumes, further factors in welding contribute to the category "health and safety." In particular, electrical, thermal and radiation hazards or the workplace ergonomics should be evaluated in the future in the pursuit of an improved working environment for welders.

In summary, the SLCA showed a sufficient wage level from which welders may support themselves financially. Potential health risks of operation depend on the respective process and are high for manual processes such as MMAW.

Table 5 The estimation of relative health effects of the welding processes

	E_p	K_b	GZ_s
MMAW	19	4	76
GMAW standard	6	2	12
GMAW modified	2	2	4
LAHW	1	1	1

4 Conclusions

This contribution evaluates the environmental impact and social influences of welding technologies by applying LCA and SLCA. It provides information to the industry as well as to the research community for developing and selecting joining technologies in view of the triple bottom line of sustainability.

The instances of environmental impact involved the selected impact categories of eutrophication potential, acidification potential, global warming potential (100 years) and photochemical ozone creation potential. The social categories were "fair salary" and "health and safety." The results serve to support industry in the development and selection of sustainable joining technologies.

The LCA results show that MMAW contributes higher environmental impact levels than GMAW or LAHW. The main cause is that MMAW consumes much more material and electricity per 1 m weld seam. Titanium dioxide consumption for electrode coating in MMAW is critical in contributing the main burden of acidification and eutrophication. GMAW is strongly influenced by filler material consumption, which is governed by the seam preparation. This is improved by using a modified spray arc, which ultimately enables a reduction of flange angles from 60° to 30°. Within the scope of the study, LAHW stands as the superior technology.

The social LCA revealed a sufficient salary for welders and potential health risks that depend on the applied process. LAHW demonstrates the lowest and MMAW the highest potential health risks that arise from fume formation. Especially manual technologies such as MMAW should therefore be limited to the minimum possible extent to reduce health risks for welders.

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