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Environmental and Social Life Cycle Assessment of welding technologies

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Abstract

Life Cycle Assessment (LCA) and Social Life Cycle Assessment (SLCA) are applied in evaluating possible social and environmental impacts of the state-of-art welding technologies, such as Manual Metal Arc Welding (MMAW), Manual Gas Metal Arc Welding (GMAW) , Automatic GMAW and Automatic Laser-Arc Hybrid Welding (LAHW). The LCA results indicate that for 1 meter weld seam, MMAW consumes the largest amount of resources (like filler material and coating on electrodes) and energy, which contributes to comparatively higher environmental impacts in global warming potential, acidification, photochemical ozone creation potential and eutrophication than other chosen processes. With regard to social aspects, the health issues and fair salary are under survey to compare the relative potential risk on human health caused by fumes in different welding technologies, and to indicate the sufficiency of current salary of welders in Germany. The results reflect that the wage status of welders is still fair and sufficient. The manual processes bring much higher potential risk of welders' health than the automatic processes, especially MMAW.

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Keywords: Fair salary; Human health; Life Cycle Assessment (LCA); Social Life Cycle Assessment (SLCA); Welding

1. Introduction

Since the increasing worldwide awareness of sustainability, sustainable manufacturing has become an ultimate goal for global governments and industries to pursue [1]. Sustainability considers the environmental, economic and social dimensions as triple bottom line theory [1, 2]. For manufacturing processes and products, environmental and social issues are often insufficiently considered and respected; however, the negative effects to environment and human can be accumulated and irreversible.

To evaluate the environmental impacts and social influences of a process or product, Life Cycle Assessment (LCA) [3-5], and Social Life Cycle Assessment (SLCA) [6] are adopted as the state-of-art methodologies. LCA is an ISO-standardized method [3-5], widely exercised to estimate the potential environmental impacts of products through the whole life cycle [5, 7, 8]. It is the most advanced and experienced 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 [6], 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 increased significantly within the last three years, the method is still considered to be in its infancy.

Welding plays the essential role in modern manufacturing. The applications are involved in many industries, for example, construction, automobile, turbine production, etc. However, the welding processes require large amounts of energy and resources, also discharge fumes causing the health effects to welders. There are limited studies, which quantify the potential negative effects on health of welders [9]. Also,

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the sufficiency of salary of welders is a topic still not fully discovered, but important to welders.

In this paper, the aim is applying LCA and SLCA on different welding processes, such as Manual Metal Arc Welding (MMAW), Manual Gas Metal Arc Welding (Manual GMAW), Automatic GMAW and Automatic Laser-Arc Hybrid Welding (LAHW) to compare the corresponding environmental impacts and the potential risk of health of welders especially caused by welding fumes since other factors such as noise, radiation and heat lack the quantitative data. Also, the wage status of welders in Germany is investigated to discuss the sufficiency to support their living. The results can help the industry to identify the crucial issues and then to improve the processes and equipment towards more sustainable alternatives.

2. Welding technologies

In production, welding is the most important joining technology. Especially in manufacturing of steel constructions, welding accounts for a main part of costs and hence value creation. Products like ships, bridges or offshore foundations are built from structural steel plates starting from 10 mm thickness. Due to the product dimensions and its respective tolerances welding is performed in a number of passes depending on the capabilities of the technology and its process parameters.

In order to reduce process times and costs high power processes are desired. One of the most highly used welding technologies is GMAW. Typical operation modes to achieve high deposition rates are spray arc and pulsed arc transfer, applied in the present study. GMAW can be executed automatic or manual. The main advantages are the ability to compensate geometry deviations and to adjust the process parameters within the process. In contrast Automatic GMAW can perform with higher welding speeds and wire feed rates. Thus deposition rate, process power and productivity exceed Manual GMAW.

LAHW offers huge potentials in increasing productivity when substituting or enhancing conventional arc processes [10], [11]. In comparison to GMAW, LAHW achieves higher welding speeds and hence higher productivity while reduced number of passes and less volume of melted material enable resource savings, lower distortion and rework. However especially in large structures with high tolerances for geometry deviations of several millimeters, gap bridging can be a critical problem. Therefore LAHW demands high accuracy edge preparation by for e.g. milling or waterjet cutting. When applying LAHW to thick materials, the limited penetration depth often requires additional filler passes with arc welding technologies. In this study LAHW is applied for root face welding followed by a GMAW filler pass to fulfill the given welding task.

MMAW with coated electrodes is a popular welding technology on building sites because it offers high flexibility and does not need a shielding gas supply. Additionally low costs for equipment and electrodes support frequent application of MMAW. On the other hand, the productivity of MMAW is low due to limited welding speeds, process powers and additional time consumptions for the change of the electrode and the removal of slag.

Besides their economic performance figures welding processes differ in the possible or needed pre and post processes. Especially edge preparation, clamping and post-weld treatment change with respect to the applied technology which has therefore huge impact on the whole production sequence. Additionally since material and energy consumption can be correlated with the molten material within the weld, process specific groove preparation and the amount of remelted and diluted base material mainly control resource consumption. Same holds true especially for multipass weld. In contrast to automatic processes manual welding incorporates health hazards coming from spatter of liquid iron, radiation, fumes or other unhealthy working positions.

So far, welding technology developments and comparisons are focused on economic indicators and therefore insufficiently consider environmental and social aspects when evaluating and choosing a process for a given welding task. Therefore this study compares four different joining processes with respect to joining a plate of 20 mm high strength structural steel. The process includes the chosen technologies as well as their specific requirements for welding execution (for e.g. root gaps or edge preparation accuracy) to produce welds of the required quality. The latter is defined by international standards and specifies the required weld properties (for e.g. from destructive, nondestructive testing and quality level for imperfections) [12], [13].

3. Methodology

3.1. Life Cycle Assessment (LCA)

Based on the ISO standard, the structure is divided into the four phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation in an iterative process [1, 3-5]. In this article, the aforementioned structure is adopted in a welding case study.

The goal of the case study is applying LCA on different welding processes to investigate their environmental impacts. The scope of the LCA aims at the welding processes themselves including the consumption of electricity, materials and gases, and the landfill of waste, but without considering machinery. The functional unit is 1 m weld seam.

According to the scope definition and the functional unit, the inventory data of the inputs and outputs of the chosen welding processes is collected. The inventory results and the technical parameters of different welding processes are shown in Table 1. Welding times, voltage, current and wire feed rate (electrode consumption in case of MMAW) including welding robot movement are measured for determination of electricity and filler material consumption. Energy efficiency of arc welding machines and laser beam source is presumed 95 % and 30 %. 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 references [9, 14-16].

In this study, CML 2001 method is adopted as the life cycle impact assessment method (as the midpoint approach). Meanwhile, GaBi 6.0 [17] is used as the software to carry out the LCA model. In the final stage, the results from assessments are interpreted and compared.

Table 1. Inventory and the parameters of the welding processes.

	MMAW	Manual GMAW
Basic Data		
Joint preparation	DV (EN ISO 9692-1)	DV (EN ISO 9692-1)
Flange angle (°)	60	60
Base material	Structural steel S960, 20 mm thick	Structural steel S960, 20 mm thick
Filler wire material	Standard coated electrode	Standard wire
Coating of electrode	Rutile	-
Type of shielding gas	-	82% Argon, 18% CO_2
Process parameters		
Average welding speed (cm/min)	20	37
Number of passes	12	6
Average power (kW)	4	8
Cross section areas of weld (mm²)	256	192
Input and output for LCA model		
Filler material consumption (g)	1,380	1,216
Shielding gas consumption (l)	-	241
Rutile consumption (g)	383	-
Energy consumption (kWh)	4.6	2.4
Welding fume emission (g)	10	5
Slag (g)	877	-
Electrode butt (g)	152	-

Table 1. Inventory and the parameters of the welding processes (cont.).

	Automatic GMAW	LAHW
Basic Data		
Joint preparation	DV (EN ISO 9692-1)	Y (EN ISO 9692-1) 14 mm root face width
Flange angle (°)	60	45
Base material	Structural steel S690, 20 mm thick	Pipeline steel X120, 20 mm thick
Filler wire material	Standard wire	Standard wire
Type of shielding gas	82% Argon, 18% CO_2	82% Argon, 18% CO_2
Process parameters		
Average welding speed (cm/min)	40	LAHW: 260 GMAW filler pass: 80
Number of passes	4	2
Average power (kW)	9.3	Root pass: 33 (Laser +GMA); Filler pass: 11
Cross section areas of weld (mm²)	158	91
Input and output for LCA model		
Filler material consumption (g)	884	155
Shielding gas consumption (l)	200	33
Compressed air for laser optics cross-jet (l)	-	249
Energy consumption (kWh)	1.9	0.9
Welding fume emission (g)	3.3	0.6

3.2. Social Life Cycle Assessment (SLCA)

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 [1, 6]. In the guidelines five main stakeholder groups (workers, consumers, local community, society and value chain actors) and 31 subcategories are described and relevant social issues are listed. As a starting point, this study focuses on the two critical social conditions: 'fair salary', 'health and safety' for the stakeholder group workers referring to welders in Germany.

By comparing the wage status of welders [18] and the non-poverty wage based on non-poverty wage calculation [19, 20], the sufficiency of salary can be recognized. The non-poverty wage reflects the real living standard status more specific than just displaying the Gross Domestic Product (GDP). Based on the poverty guidelines for a three-people family in the United States announced by the United States Cencus Bureau [20], the non-poverty wage of other countries can be deduced by multiplying the United States' non-poverty wage and the ratio of that country's GDP per capita to the United States' GDP per capita [19].

Besides, in the paper, the welding fume issues are analysed to compare the relative health and safety effects of welders in different welding processes. Welding processes generate a complex mixture of fumes (respirable and ultrafine particles) as by-products, composed of an array of metals volatilized from the welding electrode or the incorporated flux materials [21]. 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 [22-24]. Iron oxides represent the major part of fume, then chromium, manganese, and nickel account the total rest composition of the fume [21]. The iron oxide is not classifiable as a human carcinogen, but it triggers siderosis, which decreases lung capacity. Chromium (VI, insoluble) and its compounds are known as a human lung carcinogen, and 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 [23].

To represent the relative potential risk caused by fume of human health of welders, the potential risk (Gefährdungszahl, *GZ*) of the welding processes are identified in the paper. Based on the literature [9], the model simplifies and considers process-specific fume emissions in connection with the working situation. For estimating the simplified potential risk (GZ_s), the following equation 1 is used [9]:

$$GZ_s = \left(E_p \times W_p\right) \times L \times R \times K_b \quad (1)$$

E_p= emission of specific substance per functional unit;
W_p= potential effect for 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.

In the case study, the potential risk caused by per functional unit is evaluated; nevertheless, the total working time of welders is not considered. Targeting the comparison of potential risks, W_p can be assumed in the same value as 1 to represent no difference in comparison between the processes since the composition of base 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 is assumed to be identical. Besides, since the distance between welders and fume sources in different welding processes are remarkable various, the K_b levels are set correspondingly. The closer distance indicates the higher chance to inhale fume. In MMAW and manual GMAW, welders are close to the fume sources, so the levels are set as 4 [9]; in automatic GMAW, the K_b level is assumed as 2 due to there is usually with distance between welders and fume sources; in LAHW, the welding process is proceeded in welding cells, so the K_b level is defined as 1 [9].

4. Results of case study

4.1. Comparison of environmental impacts

Based on the inventory data, the life cycle impact assessments are carried out. Considering the relevance, robustness, and the practicality of impact indicators in LCA, global warming potential (100 years), acidification, photochemical ozone creation potential, and eutrophication are selected to display the environmental burdens caused by the welding processes. As shown in fig. 1. and fig. 2., MMAW contributes the highest environmental impacts among the chosen welding processes; LAHW contributes the least. Automatic GMAW has lower environmental impacts than Manual GMAW. For all indicators and technologies the sequence of technologies' results stays the same. The main reason is the difference in the consumption of electricity for welding machines and filler material. Additionally, for MMAW especially the titanium dioxide consumption (accounts 45% of coating materials) plays a key role to contribute high impacts in acidification (52%) and eutrophication (76%).

4.2. Salary status and potential effects on health

According to the GDP per capita data [25] and the non-poverty wage calculating method [19, 20, 26], the non-poverty wage of a three-people family per year in Germany in 2013 is deduced as €11,850. The latest salary survey showed on Focus Online [27] represented the average gross salary per year of welders in Germany in 2011 was € 25,980, Since the average annual salary of welders is much higher than the current estimated non-poverty wage (approximate 2 times), it is believed that welder's salary status is still sufficient to support their living.

Via the aforementioned equation 1 and the assumptions, the potential health risk, GZ_s, is highly influenced by the emission of specific substance per functional unit (E_p) and the relative distance of head/body and fume source (K_b) in the case studies. The GZ_s can be simply represented as relative $E_p \cdot K_b$. The relative E_p is calculated based on the inventory data shown in Table 1, taking the emission of LAHW as reference value to estimate the ratios. As displayed in Table 2, MMAW owns the highest GZ_s to welders among all the selected processes remarkably. Moreover, the results also indicate that the welders working in the manual processes face sharply higher risks than in automatic processes. How to protect welders sufficiently and to avoid health risks caused by fume in manual welding processes is a key issue for designing processes and improving the protecting equipment.

Table 2. The estimation of the potential health risk in the welding processes

	E_p	K_b	GZ_s
MMAW	17	4	68
Manual GMAW	8	4	32
Automatic GMAW	6	2	12
LAHW	1	1	1

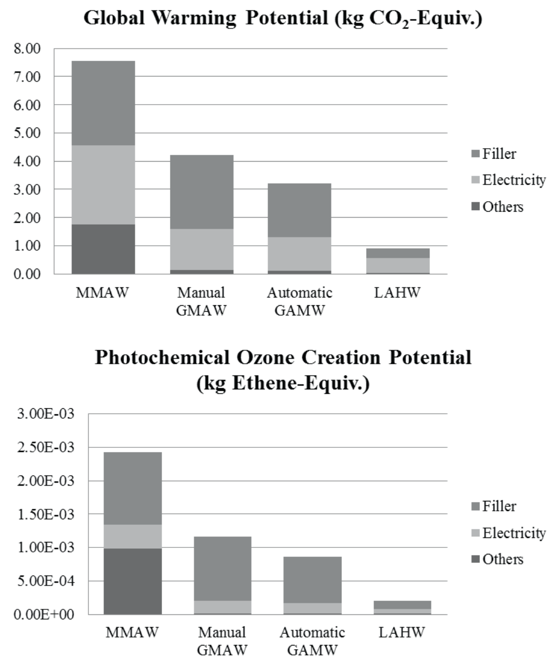

Fig. 1. Contribution on global warming potential and photochemical ozone creation potential of the welding processes

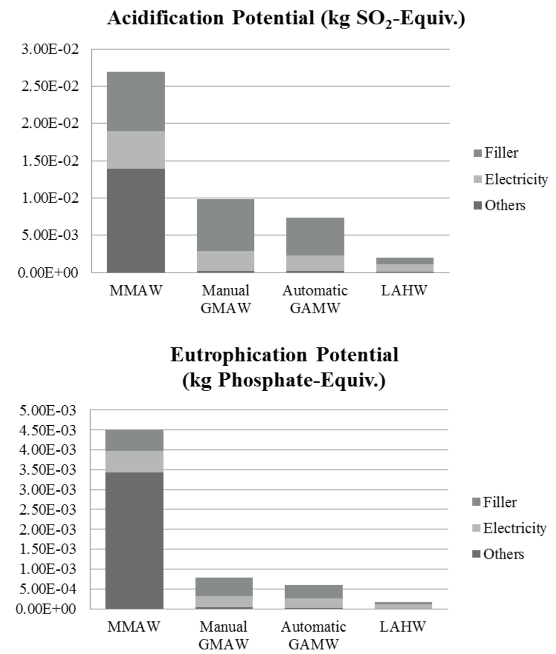

Fig. 2. Contribution on acidification and eutrophication potential of the welding processes

5. Discussion

The research reflects the comparison of environmental burdens and relative health effects of welders in different welding processes. Filler material and electricity for welding machines are the critical factors which are also well represented in the overall weld volume and the number of passes needed to fill the weld. Due to its high power density LAHW performs welding with the least number of passes, remelted material and overall weld volume. On the contrary, low welding speed and deposition rate, and consequently low productivity in MMAW lead to high welding times and hence higher environmental impacts and more fume emissions. Generally automatic processes enable more accurate and faster welding torch movement as well as higher process powers, which leads to an increase in potential health and environmental burden. These advantages can also be seen when comparing Manual and Automatic GMAW. A smaller possible root gap and higher deposition rates especially in the root passes result in less environmental impacts.

However this study does not serve as overall process comparison. Process requirements such as efforts for edge preparation, effects of different welding positions or mobility of equipment could have crucial influence on a process selection. In the LCA model, only four impact categories are presented to compare the processes; also, machinery is not considered in the study. Fume emission rates are highly dependent on the actual process and can vary from literature values. In SLCA the research is limited to focusing on workers, and the corresponding salary and health risks caused by fume. Due to lack of quantitative data, health risks from radiation, heat and noise are not considered.

However results clearly indicate that application of automatic and high power processes are favorable in terms of reducing environmental and health risks of welding processes.

6. Conclusion

The paper applies LCA and SLCA on different welding processes to compare the environmental impacts and relative potential health risks, and to evaluate salary sufficiency of welders in Germany. The contribution of the paper can provide information to industry for developing and selecting sustainable processes.

The results indicate that due to low productivity and welding speed MMAW contributes higher environmental impacts in global warming potential, acidification potential, photochemical ozone creation, and eutrophication potential, and leads to higher potential health risk of welders than other selected processes. The main cause is that MMAW consumes much more material and electricity per 1 meter welding seam, and discharges much more fume with close working distance. Also, the titanium dioxide consumption in coating in MMAW is critical to contribute main burdens in acidification and eutrophication. Adjusting coating composition and reducing the consumption of material and energy can make MMAW more environmental friendly. LAHW is the most superior process within the scope of the study. Results indicate that further developments for thick walled welds shall focus on automatic high power processes. Besides, the salary of welders in Germany is currently sufficient to support living.

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References

[1] Ya-Ju Chang, Erwin M. Schau, Matthias Finkbeiner. Application of Life Cycle Sustainability Assessment to the Bamboo and Aluminum Bicycle in Surveying Social Risks of Developing Countries. The 2nd World Sustainability Forum; November 1-302012.

[2] Pelletier N, Maas R, Goralcyk M, Wolf M-A. Towards a Life-Cycle Based European Sustainability Footprint Framework. Luxemburg2012.

[3] ISO 14040. Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006). 2. ed. July 2006 ed. Geneva: ISO; 2006.

[4] ISO 14044. Environmental management - Life cycle assessment - Requirements and guidelines (ISO 14044:2006). Geneva: ISO; 2006.

[5] Erwin M. Schau, Ya-Ju Chang, René Scheumann, Matthias Finkbeiner. Manufactured products – how can their life cycle sustainability be measured? A case study of a bamboo bicycle. The 10th Global Conference on Sustainable Manufacturing; Istanbul, Turkey2012.

[6] United Nations Environment Programme. The Guidelines for Social Life Cycle Assessment of Products. Catherine Benoît, UQAM/CIRAIG, Bernard Mazijn, Ghent University, editors. Druk in de weer (Belgium): United Nations Environment Programme,; 2009.

[7] Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A, van Oers L, Sleeswijk AW, Suh S, Udo de Haes HA, de Bruijn H, van Duin R, Huijbregts MAJ. Handbook on life cycle assessment - Operational guide to the ISO standards. Tukker A, editor. Dordrecht: Kluwer Academic Publishers; 2002.

[8] Klöpffer W, Grahl B. Ökobilanz (LCA): Ein Leitfaden für Ausbildung und Beruf. Weinheim: Wiley-vch; 2009.

[9] Vilia Elena Spiegel-Ciobanu. Occupational health and safety regulations with regard to welding and assessment of the exposure to welding fumes and of their effect. Welding and Cutting. 2012;11(1).

[10] Denney P. What You Should Know about Hybrid Laser Arc Welding - Take a look at the pros and cons of this unique combination of lasers and gas metal arc welding. Weld J. 2013;Jg. 2013(1):38-41.

[11] Gook SG, A.; Rethmeier, M. Hybrid laser arc welding of X80 and X120 steel grade. Science and Technology of Welding and Joining. 2014;19(1):10.

[12] DIN. DIN EN ISO 15614-1 Anforderung und Qualifizierung von Schweißverfahren für metallische Werkstoffe – Schweißverfahrensprüfung. Teil 1: Lichtbogen- und Gasschweißen von Stählen und Lichtbogenschweißen von Nickel und Nickellegierungen2011.

[13] DIN. DIN EN ISO 5817 Schweißen – Schmelzschweißverbindungen an Stahl, Nickel, Titan und deren Legierungen (ohne Strahlschweißen) – Bewertungsgruppen von Unregelmäßigkeiten (ISO/DIS 5817:2012). Beuth Verlag GmbH; 2012.

[14] Sascha Rose, Michael Schnick, Uwe Füssel. Cause-and-effect chains of fume formation in GMAW and possibilities of fume reduction by using new welding processes. 65rd Annual Assembly & International Conference of the IIW, Commission XII Arc Welding Processes and Production Systems; Denver2012.

[15] B. J. QUIMBY, G. D. ULRICH. Fume formation rates in gas metal arc welding. Welding Journal. 1999;78(4):142-9.

[16] Geoff Melton. The Effect Of Metal Transfer Modes On Welding Fume Emission In MIG/MAG Welding. Eighth European Conference on Joining Technology; Croatia2012.

[17] PE Interational AG. GaBi Software. PE Interational AG,; 2014 [cited 2014 April 29]; Available from: http://www.gabi-software.com/deutsch/index/.

[18] International Labour Organization. LABORSTA Internet. International Labour Organization,; 2010 [cited 2014 April 30]; Available from: http://laborsta.ilo.org/.

[19] Sweatfree Communities. Non-Poverty Wages for Countries Around the World. 2009 [cited 2014 April 30]; Available from: http://www.sweatfree.org/nonpovertywages.

[20] United States Cencus Bureau. Poverty Thresholds by Size of Family and Number of Children. United States Cencus Bureau; 2014 [cited 2014 April 30]; Available from: http://www.census.gov/hhes/www/poverty/data/threshld/index.html.

[21] James M. Antonini, Alikabar A. Afshari, Sam Stone, Bean Chen, Diane Schwegler-Berry, W. Gary Fletcher, W. Travis Goldsmith, Kurt H. Vandestouwe, Walter McKinney, Vincent Castranova, David G. Frazer. Design, construction, amd characterization of a novel robotic fume generator and inhalation exposure system for laboratory animals. Journal of Occupational and Environmental Hygiene. 2006;3:194-203.

[22] American Federation of State County and Municipal Employees. Welding Hazards2014.

[23] Matthew Gonser, Theodore Hogan. Arc Welding Health Effects, Fume Formation Mechanisms, and Characterization Methods. In: Sudnik PW, editor. Arc Welding: InTech; 2011.

[24] Canadian Centre for Occupational Health & Safety. Occupations & Workplaces: Welders. Canadian Centre for Occupational Health & Safety; 2013 [cited 2014 April 22]; Available from: http://www.ccohs.ca/oshanswers/occup_workplace/welder.html.

[25] World Bank. GDP per capita. World Bank; 2014 [cited 2014 April 30]; Available from: http://data.worldbank.org/indicator/NY.GDP.PCAP.CD.

[26] European Central Bank. Exchange Rates. 2014 [cited 2014 April 30]; Available from: http://sdw.ecb.europa.eu/home.do.

[27] FOCUS Online. 150 Berufe im Gehaltsüberblick. FOCUS Online,; 2012 [cited 2014 May 2]; Available from: http://www.focus.de/finanzen/karriere/tid-28806/titel-deutschlands-groesster-gehalts-report-150-berufe-im-gehaltsueberblick_aid_890328.html.