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Sustainability Assessment and Life Cycle Analysis of Welding Processes: Focus on GMAW and SMAW

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Abstract
Sustainable development is defined as a solution to meet the needs of the current generation without jeopardizing the needs of future generations, considering the critical role it plays in maintaining all ecosystems. In this regard, it is essential to pay attention to three environmental, economic, and social aspects simultaneously. In this research, the sustainability of Gas Metal Arc welding and Shielded Metal Arc welding was studied according to the wide application of welding as a critical production method in the industry. The results showed that Gas Metal Arc welding has less waste of energy, raw materials, and electrodes due to continuous electrodes and the possibility of automatic welding. On the other hand, Shielded Metal Arc welding due to low thermal efficiency, electrode waste, the release of toxic gases due to the burning of the electrode coating, and also the need to change the electrode, has a lower sustainability performance.

Keywords: *Environmental impacts, Life cycle assessment (LCA), Sustainable development, Shielded metal arc welding (SMAW), Gas metal arc welding (GMAW).*

Introduction

Welding is a production method that connects two metallic or non-metallic materials and creates a continuous member. The goal is to achieve a connection with properties similar to the base metal [1-3]. Welding with various methods has the most powerful application for connecting and integrating parts, especially in cases without disassembling them. It introduces the speed of operation, cheapness, simplicity, high quality of welded joints, and the possibility of mechanization of welding as one of the best joining methods [4,5]. In general, welding is used in addition to building structures, oil and gas industries, shipbuilding, and automotive industries as one of the most essential joining methods in the nuclear, electronic, and chemical industries [6]. The arc temperature in the welding process can reach about 20,000 centigrade, which, in addition to breaking down the compounds related to the base metal and the filler metal into their constituent atoms, also ionizes the shielding gas. Therefore, the presence of toxic gases and vapors, as well as metal vapors, can be hazardous to human health. In addition, hazards such as ultraviolet and infrared radiation from arcs can damage body tissues [7-11].

On the other hand, although welding is essential in modern manufacturing, it also requires a lot of energy and resources. According to estimates, the industry sector accounts for more than 50% of electricity consumption worldwide. The share of energy consumed by energy production systems such as welding and other production processes is approximately 70% of this energy. [12]. Therefore, due to the high consumption of power in this sector and the broad application of the welding method, it is essential to deal with environmental issues, problems, and damages along with technological advances. Existing research focuses mainly on the technical and economic aspects of the welding process, and environmental and social factors are rarely considered. However, research has been done in this field [13-20]. Although this research examined essential sustainable manufacturing strategies to reduce the environmental impact of welding processes, such as energy consumption reduction, waste minimization, process parametric optimization, and employee skill and training, a clear picture of the environmental impact and sustainable criteria of welding technologies was not provided. This article used LCA to evaluate the life cycle of gas metal arc welding and shielded metal arc welding. These welding methods were examined and compared in terms of ecological, sociological, and technological indicators.

Shielded metal arc welding

Shielded metal arc welding (SMAW) is a process in which the molten metal from the melting of the coated metal electrode is transferred through the arc to the molten pool and mixed with the base metal. The gas protects the end of the electrode and the molten puddle from burning the electrode coating compounds. With the SMAW welding machine, it is possible to weld parts with different thicknesses from two millimeters to several feet. SMAW welding with coated electrodes is a popular welding technology in building structures because it is easily portable due to low equipment and does not require a shielding gas source. But on the other hand, productivity in the SMAW welding method could be higher due to the limitation of welding speed, process power, and additional time for electrode replacement and slag removal. This process is used for welding various metals and alloys such as aluminum, stainless steel, and nickel. However, this process can also be used for welding ferrous and non-ferrous metals [21,22]. The shielded metal arc welding process is shown in Fig.1.

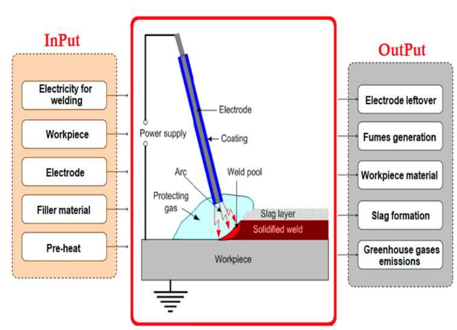

Fig. 1: The shielded metal arc welding process [14].

Gas metal arc welding

Gas metal arc welding (GMAW) is one of the types of arc welding methods in which shielding gas is used to protect the weld pool from environmental pollutants. In this welding method, one pole is the current of the workpiece, and the other is a solid metal melting wire produced continuously without powder coating and has an alloy close to the base metal alloy. This type of welding is usually done manually and automatically. The movement of the electrode wire toward the workpiece and the welding pool is controlled by the wire feeding device, and the wire is guided to the welding pool at a certain speed by two or four pulleys. This welding method has high productivity and good quality in welding joints. In the GMAW welding method, if a neutral gas such as argon or helium is used to protect the weld pool, it is called MIG, and if an active gas such as carbon dioxide is used, the welding method is called MAG. Of course, in some cases, the combination of neutral gases with active gases such as CO_2 and O_2 with a low percentage is used for welding [6,23,24]. GMAW can weld most metals, such as steel and aluminum. Due to the lack of cleaning deposits, welding slag, and a continuous electrode, it has a very high-efficiency rate compared to other welding methods, such as shielded metal arc welding. Therefore, according to these features, GMAW welding has become one of the most widely used industries, such as oil, gas, petrochemical, shipbuilding, automotive sectors, etc. [5, 23, 25, 26]. The gas metal arc welding process is shown in Fig 2.

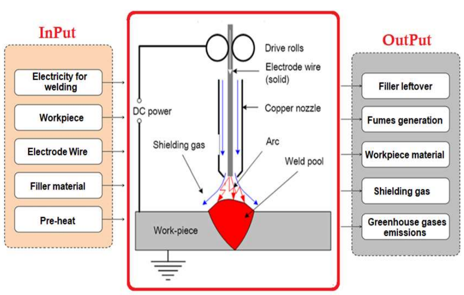

Fig. 2: The gas metal arc welding process [14].

Experimentation and data collection

Since the global awareness of sustainability concepts increased, sustainable production and development have become the ultimate goal of governments and international industries. Sustainability considers environmental, economic, and social dimensions a triple theory [27,28]. To evaluate the ecological impacts and social impacts of a process or product, life cycle assessment (LCA) is adopted as an advanced method [29-32]. LCA is a standard method that is widely applied to estimate the environmental impact of products throughout their entire life cycle; based on the ISO standard, its structure is divided into four stages: definition of the goal and scope, life cycle analysis, evaluation Life cycle impact, and interpretation in an iterative process [31-34]. This research investigated the life cycle analysis of GMAW and SMAW welding methods and their environmental effects, including electricity consumption, materials and gases, and waste disposal. The boundaries of the system were determined (Fig 3), which includes the production of consumable raw materials such as base metal, filler, shielding gas, and electrical energy as process inputs and smoke production, waste of raw materials and consumable electrodes, and protecting gas consumption as process outputs. Are. The use and end-of-product life phases should be considered in this review of machines and equipment and the maintenance stages. The inventory results and technical parameters of various welding processes are shown in Table 1. Welding procedure specification (WPS) and ISO 14040 standards were used in data collection and analysis [35,36].

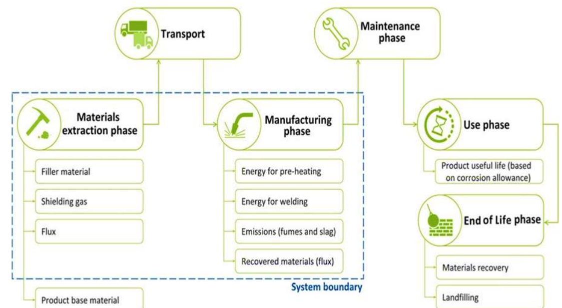

Fig. 3: Determined boundaries of the system in welding processes [21,22].

Table 1: Input data of GMAW and SMAW welding processes.

	SMAW	*GMAW*
Base metal	**St37**	**St37**
Joint angle	**60º**	**60º**
Root gap	**3 mm**	**3 mm**
Root face	**4 mm**	**4 mm**
Thickness	**25 mm**	**25 mm**
Length	**1 m**	**1 m**
Number of passes	**8**	**15**
The cross-section area	**457.69 mm^2**	**457.69 mm^2**
Preheat temperature	**50 ºC**	**80 ºC**
Welding speed	**0.37 m/min**	**0.08 m/min**
Power	**8.7 kW**	**3.47 kW**

Results and discussion

Life cycle assessment

Life cycle assessment is a widely applied standard method for estimating the potential environmental impacts of products over their entire life cycle. The results related to life cycle assessment and analyzed with SimaPro version/8.05.13 software for GMAW and SMAW welding processes were performed and shown in Fig 4. As the results show, climate changes related to the SMAW process are more because: firstly, more electrical energy is consumed during this process, and secondly, it also consumes more filler. And the changes related to climate in the GMAW process are almost 50% of the values created in the SMAW welding method. These results are also noticeable in the destruction of the ozone layer with the same percentage. The destruction of fossil resources is also higher in SMAW welding due to higher electric current consumption and lower efficiency [21,22]. According to the type of welding process, the arc temperature may reach up to 20,000 centigrade, and this temperature will easily be able to decompose the base metal and filler metal compounds into their constituent atoms in addition to the ionization of the shielding gas. Also, the electric arc can cause the generation of high-energy ultraviolet and infrared rays, which are harmful to aquatic body tissues [7-11]. As the results show, the amount of ion radiation and metal destruction in the SMAW welding process is also higher.

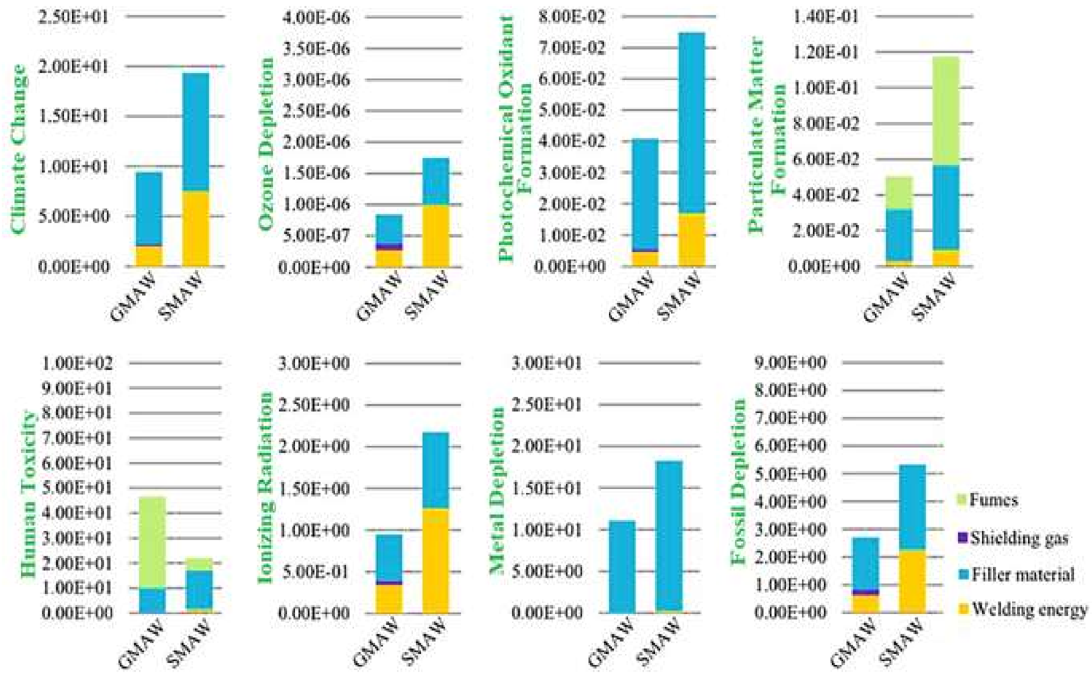

Fig. 4: The life cycle assessment results in GMAW and SMAW welding processes [21].

Sustainable development

Sustainable development is mainly defined as providing for the needs of the present generation without compromising the needs of future generations. Sustainable development plays a crucial role in maintaining all living ecosystems because it is not only for humans but also includes all living organisms in the environment. When analyzing sustainability for a particular process, it is essential to simultaneously consider all three aspects, environmental, economic, and social. In the form of various government laws and regulations, the production sector is constantly under much pressure to improve the environmental performance of different production operations [37-40]. In addition to strict environmental laws, the manufacturing industry has also realized that improving ecological performance can bring long-term economic benefits and better survival in the market [41,42]. The idea of sustainable development deals with advancing human development while preserving the environment simultaneously [43,44]. Improving the environmental performance of a production process means reducing input energy consumption, reducing the flow of hazardous substances in and out, improving working conditions, reducing occupational safety risks, and optimizing costs. The concept of sustainable development in welding processes must be defined in the collective framework of diverse economic, environmental, and social aspects together and simultaneously [21,22]. In terms of economic indicators, it is intended to reduce the cost of raw materials, shielding gas, and electrodes, as well as improve the efficiency of the welding process per the amount of electricity used. From the environmental aspect, reducing waste, less consumption of consumables, and reducing the environmental effects caused during the processing and production of these materials are considered. Finally, the social aspect considers improving the level of well-being and health of operators and reducing toxic and dangerous production gases that directly affect the health of workers as the final goal. Therefore, by observing the established principles and purposes, it can be expected that welding production will reach a stable state. The model of sustainable development in welding processes is shown in Fig 5**.**

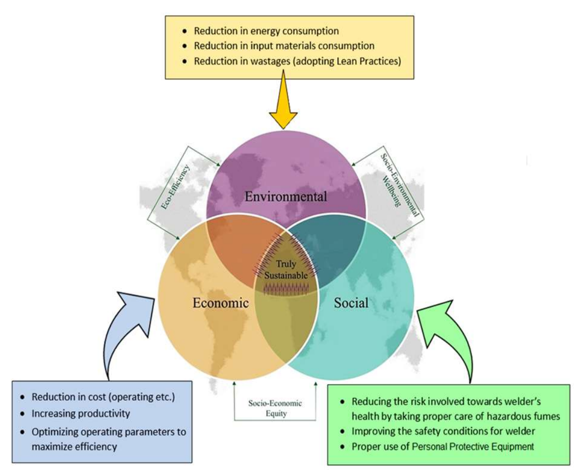

Fig. 5: Model of sustainable development in welding processes [45].

To check sustainability from the environmental aspect, ten indicators representing the relationship between the environment and humans are evaluated and scored under the sub-group of Ecological parameters (Table 2). In this method, the scores will be between zero and one, a score of zero means acute conditions from the environmental point of view, and a score of one will be sustainability for the environment [46]. In the meantime, the availability indicator includes easy access to welding devices and raw materials to perform the welding process and the initial price of the required materials. The second indicator is the degree of adaptability and less waste to produce the materials needed to perform the welding process [47]. The third indicator is the environmental capacity of welding processes. Due to the limited resources for processing raw materials such as base metal, consumable electrodes, etc., it is not possible to consider the top score in this indicator for both welding methods. Another indicator is the timeline, novelty, and progress of the process. In the case of SMAW welding, all the necessary innovations in this welding method have been provided so far. Still, the GMAW welding method will have the possibility of further progress due to the case of automation of the process. 21, 22, 48]. The efficiency rate indicator of energy and raw materials is always higher than the SMAW method due to the high efficiency of the GMAW welding method [21,22]. SMAW welding, due to the amount of smoke created during welding and the amount of electrical energy being higher along with the low efficiency, has more polluting effects on the environment, and it can be concluded that it will affect the balance of the local ecosystem more. Due to the ability to quickly move the device and equipment and cheaper maintenance compared to expensive GMAW welding equipment, the SMAW welding process has a higher score in terms of location and endurance indicators. [21,22,49].

Table 2: Ecological indicators in GMAW and SMAW welding processes.

Ecological indicators	*Shielded metal arc welding*		*Gas metal arc welding*	
Availability	The equipment used is simple, cheap and easy to carry anywhere	**0.90**	High-pressure cylinders shielding gas	**0.60**
Adaptability	The production process of electrodes	**0.40**	High-pressure cylinders, high electrode efficiency	**0.70**
Environmental Capacity	Climate change, human toxicity, metal depletion	**0.30**	Metal depletion	**0.80**
Timeline	Fossilized, climate change, human toxicity	**0.10**	No Slag, high efficiency, fully automated	**0.80**
Material Rate	Electrode leftover, low efficiency	**0**	Loss of shielding gas, high efficiency	**0.90**
Energy Rate	Low-efficiency %60	**0.60**	High-efficiency %80-%98	**1**
Pollution Rate	Climate change, human toxicity, emissions of welding fumes	**0**	The GMAW process performs better t han the SMAW	**0.90**
Location	Easy to carry anywhere	**0.80**	Workshop	**0.10**
Ecological Balance	Emissions of welding fumes, electrode leftover, slag	**0**	Shielding gas, filler metal compounds	**0.80**
Endurance	Quick set-up	**1**	Welding equipment is more complex, more costly	**0.30**

The other ten indicators included in the Sociological indicators subgroup are related criteria between society and the economy. These indicators consider social benefits along with economic benefits and examine and study both social and economic dimensions at the same time. The results of this review and scoring for these ten parameters are shown in Table 3. Regarding economic indicators, society's view of this welding method is more favorable due to the cheaper SMAW welding equipment, widespread use in construction, and availability. But, the GMAW welding method, due to the automatic process, reduction of operator error during welding, high efficiency, and wide application in large industries such as oil and gas pipe welding, the view of large manufacturing companies are always focused on using this process.

Finally, the other ten indicators that express technical criteria and are placed in the subgroup of technological indicators were studied. These indicators are shown in Table 4. In the welding process, electrical energy is converted into heat, which is used to melt the base metal and join it. In terms of efficiency and energy indicators, the SMAW welding process has a low score due to low efficiency, heat loss, spatter and spark [5,6,21]. In terms of research and evolution indicators, GMAW welding due to the very little waste, high thermal efficiency, the welding of a wide range of metals and alloys [50,51], the possibility of automation, and application with high production rate, a high score can be expected for this process [37-39]. The review and scoring of 30 determined indicators show that (Fig 6), the GMAW process scores 6.9, 7.1, and 7.5 in all three Ecological, Sociological, and Technological groups. This process is better than the SMAW welding method.

Table 3: Sociological indicators in GMAW and SMAW welding processes.

Sociological indicators	*Shielded metal arc welding*		*Gas metal arc welding*	
Economics	Electrode leftover, low efficiency	**0.80**	Welding equipment is more costly	**0.40**
Policy	Fossilized	**0.20**	Fully automated, oil and gas industry	**0.90**
Human Resources	Less labor is needed	**0.20**	More labor is needed	**0.90**
Public Opinion	The equipment used is cheap, easy to use	**1**	Welding equipment is more costly, fully automated	**0.40**
Environmental Obligation	SMAW causes adverse health effects, emissions of welding fumes	**0.10**	UV radiation, workshop, welding Procedure Specification	**0.90**
Living Standards	Construction industry	**0.90**	More labor is needed	**0.60**
Human Convenience	Construction industry	**1**	The automotive industry, shipbuilding	**0.80**
Future Development	Fossilized	**0.10**	Fully automated,	**0.80**
Per Capita Demand	Lower equipment cost than GMAW	**0.90**	The automotive industry, shipbuilding	**0.50**
Lobbying	Ordinary people	**0.10**	Fully automated, automotive industry	**0.90**

Table 5: Technological indicators in GMAW and SMAW welding processes.

Technological Indicators	*Shielded Metal Arc welding*		*Gas Metal Arc welding*	
Net Energy Consumption	easy to carry anywhere, quick set-up	**1**	Welding equipment is more complex	**0.30**
Exergy	low efficiency	**0.50**	High efficiency	**0.90**
Efficiency	Low-efficiency %60	**0.60**	High-efficiency %80-%98	**1**
Design	Easy to use, quick change from one material to another	**1**	Welding equipment is more costly, welding equipment is more complex	**0.50**
Research	Fossilized	**0**	Welding different types of metals and alloys	**0.90**
Demonstration	It can be used anywhere, easy to carry anywhere	**0.90**	Fully automated	**0.60**
Commercialization	Quick set-up	**1**	Welding equipment is more costly	**0.60**
Impact	Fossilized	**0.20**	High efficiency	**0.80**
Evolution	Fossilized	**0**	Wide researches	**1**
Environmental Limitation	Emissions of welding fumes, electrode leftover, slag	**0.20**	Climate change, human toxicity	**0.90**

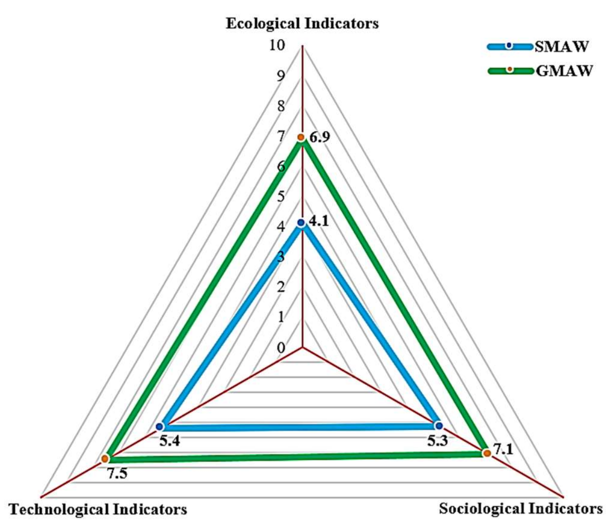

Fig. 6: The results of examining GMAW and SMAW welding processes in terms of technological, sociological, and ecological indicators.

Conclusions

Welding is used in various industrial sectors, from construction in the building sector to large and diverse industries such as automotive, aerospace, shipbuilding, and nuclear. Due to the high energy consumption in welding processes, a significant portion of energy consumption in the industrial sector is allocated to this production method. Sustainable development encompasses three aspects of the environment, economy, and society in every production industry. Sustainable development in welding processes involves reducing energy consumption, reducing the production of gases and hazardous substances, improving working conditions, and optimizing costs. In addition to reviewing the life cycle analysis of GMAW and SMAW welding, this article discusses the current status of sustainable development in welding processes. The results showed:

- In life cycle analysis, the GMAW welding process performs better than SMAW. GMAW welding has the least environmental impact due to less energy consumption.
- Ecological indicators, which show the relationship between humans and the environment, show that GMAW welding, with a score of 6.9 out of 10, is better than SMAW welding.
- Sociological indicators, which represent the interactions between society and the economy, showed that GMAW welding is better than SMAW welding due to the automation of the process, reduction of operator error, and high efficiency.
- Technological indicators, proved the better performance of GMAW welding compared to SMAW welding, scoring 7.5 out of 10.

Reference

[1] M.I. Khan, 2007. “Welding Science and Technology”. *New Age International (P) Limited*.
[2] R.W. Messler Jr, 2008. “Principles of welding: processes‹ physics, chemistry and metallurgy”. *John Wiley & Sons*.
[3] P.T. Houldcroft, R. John, 2001. “Welding and Cutting: A Guide to Fusion Welding and Associated Cutting Processes”. *Elsevier*.
[4] D. Paniagua-Mercado, Tl, S. David, 2003. “Physical processes in fusion welding”. *Reviews of modern physics*, 67 85.
[5] Kou, Sindo, 2003. “Welding metallurgy’. *New Jersey*, USA, 431.446: 223-225.
[6] Norrish, J. 2006. “High-energy density processes. Advanced Welding Processes”. J. Norrish, Ed. *Elsevier*, 136-164.
[7] Fatmasari, Ikka Fitria Feby, Siti Musyarofah, and Baju Widjasena, 2019. “the relationship between complience use PPE eyes with metal welding chips in eyes welders in the welding workshop in boja”. *Jurnal Formil (Forum Ilmiah) KesMas Respati e-ISSN*, Vol. 4, No. 2.
[8] Adewoye, Kayode Rasaq, et al., 2013. “Knowledge on the health effects of welding smoke, use of ppe amongPPEectric-arc welders in Ilorin south, north central Nigeria”. *Journal of Asian Scientific Research,* 3.9, 924-932.
[9] Gonser, Matthew, and Theodore Hogan,2011. “Arc welding health effects, fume formation mechanisms, and characterization methods”. *Arc welding*, 299-320.
[10] Dixon, Anthony J., and Brian F. Dixon, 2004. “Ultraviolet radiation from welding and possible skin and ocular malignancy risk”. *Medical journal of Australia,* 181.3, 155-157.
[11] Wanjari, Mayur Bhaskarrao, and Pratibha Wankhede, 2020. “Occupational hazards associated with welding work influence the health status of welders”. *International Journal of Current Research and Review*, 12.23, 51-55.
[12] Woolley, Elliot, Yang Luo, and Alessandro Simeone, 2018. “Industrial waste heat recovery: A systematic approach”. Sustainable *Energy Technologies and Assessments,* 29, 50-59.
[13] Ardente, Fulvio, et al., 2005. “Life cycle assessment of a solar thermal collector: sensitivity analysis, energy, and environmental balances”. *Renewable Energy,* 30.2, 109-130.
[14] Douglas, C. A., G. P. Harrison, and J. P. Chick, 2008. “Life cycle assessment of the Seagen marine current turbine”. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment,* 222.1, 1-12.
[15] Zukauskaite, A., et al., 2013. “Environmental and human health issue of welding in the shipyard”. *Transport Means 17th International Conference*, Vol. 2013.
[16] Zhang, Lei, et al.,2016. “Greenhouse gases (GHG) emissions analysis of manufacturing of the hydraulic press slider within forging machine in China”. *Journal of Cleaner Production*, 113, 565-576.
[17] Peng, Shitong, et al.,2016. “Life cycle assessment of a large-scale centrifugal compressor: A case study in China”. *Journal of Cleaner Production*, 139, 810-820.
[18] Alkahla, Ibrahim, and Salman Pervaiz, 2017. “Sustainability assessment of shielded metal arc welding (SMAW) process”. *IOP conference series: materials science and engineering*, Vol. 244, No. 1, IOP Publishing.
[19] Sproesser, Gunther, Andreas Pittner, and Michael Rethmeier, 2016. “Increasing performance and energy efficiency of gas metal arc welding by a high power tandem process”. *Procedia Cirp*, 40, 642-647.
[20] Shrivastava, Amber, Manuela Krones, and Frank E. Pfefferkorn, 2015. “Comparison of energy consumption and environmental impact of friction stir welding and gas metal arc welding for aluminum”. *CIRP Journal of Manufacturing Science and Technology*, 9, 159-168.
[21] Favi, Claudio, et al., 2019. “A data framework for environmental assessment of metal arc welding processes and welded structures during the design phase”. *The International Journal of Advanced Manufacturing Technology*,105.1, 967-993.
[22] Favi, Claudio, Federico Campi, and Michele Germani, 2019. “Comparative life cycle assessment of metal arc welding technologies using engineering design documentation”. *The International Journal of Life Cycle Assessment,* 24.12, 2140-2172.
[23] I.A. Ibrahi, S.A. Mohama, A. Amir, A. Ghalib, 2012. “The Effect of Gas Metal Arc Welding (GMAW) processes on different welding parameters”. *Procedia Engineering*, 41 1502-1506.
[24] M.S. Wêglowski, Y. Huang, Y. Zhang, 2008. “Effect of welding current on metal transfer in GMAW”. *Archives of Materials Science and Engineering*, 33, 49-56.
[25] Khan, Md Ibrahim, 2008. “Welding science and technology”. *New Age International*.

[26] Weman, Klas, 2011. "Welding processes handbook". *Elsevier*.

[27] Ya-Ju Chang, Erwin M. Schau, Matthias Finkbeiner, 2012. "Application of Life Cycle Sustainability Assessment to the Bamboo and Aluminum Bicycle in Surveying Social Risks of Developing Countries". *The 2nd World Sustainability Forum*, 1-30.

[28] Pelletier, Nathan, et al., 2012. "Towards a life-cycle based european sustainability footprint framework". *Theory, Concepts, Applications. Joint Research Centre Institute for Environment and Sustainability, Luxembourg, European Union.*

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

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

[31] Erwin M. Schau, Ya-Ju Chang, René Scheumann, Matthias Finkbeiner, 2012. "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, Turkey.

[32] Benoît, Catherine, et al., 2010. "The guidelines for social life cycle assessment of products: just in time". *The international journal of life cycle assessment,* 15, 156-163.

[33] Guinée, Jeroen B., ed., 2002. "Handbook on life cycle assessment operational guide to the ISO standards". *Springer Science & Business Media*, Vol. 7.

[34] Klöpffer, Walter, and Birgit Grahl. Ökobilanz (lca), 2009. "Ein leitfaden für ausbildung und beruf". *John Wiley & Sons*.

[35] ISO, ISO14040, 2006. "14040." Environmental management—life cycle assessment—principles and framework". 235-248.

[36] International Organization for Standardization, 2006. "Environmental management: life cycle assessment; requirements and guidelines". *Geneva, Switzerland: ISO*, Vol. 14044.

[37] Jawahir, I. S., and O. W. Dillon Jr., 2007. "Sustainable manufacturing processes: new challenges for developing predictive models and optimization techniques". *Proceedings of the first international conference on sustainable manufacturing, Montreal*, Canada.

[38] Ghosh, Sudarsan, and P. Venkateswara Rao, 2015. "Application of sustainable techniques in metal cutting for enhanced machinability: a review". *Journal of Cleaner Production*, 100, 17-34.

[39] Evans, Annette, Vladimir Strezov, and Tim J. Evans, 2009. "Assessment of sustainability indicators for renewable energy technologies". *Renewable and sustainable energy reviews,* 13.5, 1082-1088.

[40] Afgan, Naim H., and Maria G. Carvalho, 2004. "Sustainability assessment of hydrogen energy systems". *International journal of hydrogen energy,* 29.13, 1327-1342.

[41] Kaebernick, Hartmut, and Sami Kara, 2006. "Environmentally sustainable manufacturing: a survey on industry practices". *Proceedings of 13th CIRP international conference on life cycle engineering*, Vol. 31.

[42] Lélé, Sharachchandra M., 1991. "Sustainable development: a critical review". *World Development*, 19.6, 607-621.

[43] Gutowski, Timothy G., 2011. "Manufacturing and the Science of Sustainability". *Glocalized Solutions for Sustainability in Manufacturing: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Technische Universität Braunschweig, Braunschweig, Germany*, May 2nd-4th, 2011, Springer Berlin Heidelberg.

[44] Thiriez, Alexandre, and Timothy Gutowski, 2006. "An environmental analysis of injection molding". *Proceedings of the 2006 IEEE International Symposium on Electronics and the Environment*.

[45] Alkahla, Ibrahim, and Salman Pervaiz, 2017. "Sustainability assessment of shielded metal arc welding (SMAW) process". *IOP conference series: materials science and engineering*, IOP Publishing, Vol. 244, No. 1.

[46] Gnanapragasam, Nirmal V., Bale V. Reddy, and Marc A. Rosen, 2010. "A methodology for assessing the sustainability of hydrogen production from solid fuels". *Sustainability,* 2.6, 1472-1491.

[47] Golbabaei, Farideh, and Monireh Khadem, 2015. "Air pollution in welding processes—assessment and control methods". *Current air quality issues*, 33-63.

[48] Castleman, Barry I., and Grace E. Ziem, 1664. "American conference of governmental industrial hygienists: Low threshold of credibility". *American journal of industrial medicine*, 26.1,133-143.

[49] Chang, Ya-Ju, et al., 2015. "Environmental and social life cycle assessment of welding technologies". *Procedia Cirp*, 26, 293-298.

[50] Katsas, S., J. Nikolaou, and G., 2006. "Papadimitriou, Microstructural changes accompanying repair welding in 5xxx aluminum alloys and their effect on the mechanical properties". *Materials & Design*, 27(10), p. 968-975.

[51] Liang, Y., et al., 2018. "Effect of TIG current on microstructural and mechanical properties of 6061-T6 aluminum alloy joints by TIG–CMT hybrid welding". *Journal of Materials Processing Technology*, 255, p. 161-174.