Sustainability assessment of shielded metal arc welding (SMAW) process

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Abstract. Shielded metal arc welding (SMAW) process is one of the most commonly employed material joining processes utilized in the various industrial sectors such as marine, ship-building, automotive, aerospace, construction and petrochemicals etc. The increasing pressure on manufacturing sector wants the welding process to be sustainable in nature. The SMAW process incorporates several types of inputs and output streams. The sustainability concerns associated with SMAW process are linked with the various input and output streams such as electrical energy requirement, input material consumptions, slag formation, fumes emission and hazardous working conditions associated with the human health and occupational safety. To enhance the environmental performance of the SMAW welding process, there is a need to characterize the sustainability for the SMAW process under the broad framework of sustainability. Most of the available literature focuses on the technical and economic aspects of the welding process, however the environmental and social aspects are rarely addressed. The study reviews SMAW process with respect to the triple bottom line (economic, environmental and social) sustainability approach. Finally, the study concluded recommendations towards achieving economical and sustainable SMAW welding process.

1. Introduction
Welding process joins materials by achieving localized coalescence under the action of heat, pressure or both. The localized coalescence help the faying surfaces to fuse in to each other and make single unit [1]. Welding is mainly utilized to fabricate different constructional structures by means of joining metallic elements. Welding process is available in all small or large scale workshops, where it is employed to repair the problematic parts as well. A good portion of production sector is based on the tasks related to the applications of different joining techniques. Welding has an advantage that it has been practiced in the space as well. It the fabrication process that has practical application in air, water and space. Welding is employed in the different industrial sectors such as automotive, aerospace, ship-building, construction, nuclear, power generation, electronics, house-hold appliances, petrochemicals and machinery fabrication etc. [1, 2]. In the form of different governmental rules and regulations, production sector is under high pressure to improve the environmental performance of different manufacturing operations [3, 4]. Besides the strict environmental legislations, production sector has also realized that improving environmental performance can bring long term economic benefits and better survival in the market [5]. The concept of sustainable development (SD) is gaining popularity in the manufacturing sector as well to explore the possibility of achieving development and imporved environmental performance simultaneously [6]. The idea of sustainable development (SD) deals with progressing the human development while sustaining the environment at the same time [7, 8]. Improving the environmental...
performance of a manufacturing process means reducing input energy consumption, reducing hazardous input and output material flows, improving work conditions, reducing risks related to the occupational safety and optimizing related costs etc [9]. Several researchers have focused their research work towards the betterment of the welding process in terms of increasing process efficiency, cost optimization, social aspects and environmental concerns. There is a need to characterize sustainability for the welding processes under the collective framework of different economic, environmental and social aspects together. As per literature, the sustainability assessment method where all economic, environmental and social aspects are collectively considered is termed as triple bottom line (TBL) or three pillar approach [10]. This study reviews and characterizes sustainability for the SMAW process using TBL methodology. The study was helpful in providing a collective sustainability overview using economic, environmental and social aspects. In the end, the study also recommends future directions for the research work to make SMAW process more environment friendly in nature.

As addressed earlier, welding operation is one of the most commonly used joining process in the metal fabrication industry. Figure 1 represents the input output inventory for the SMAW process. To perform the SMAW operation, electric current flows through the electrode and the workpiece material in the form of electric arc. The flow of electricity from electrode to workpiece generates heat on both sides and droplets of molten metal transfers to the molten puddle to fuses them together. Once the electrode moves away from the processing region the welding bead gets solidifies and welding operation completes[11, 12]. The electrode is generally coated with the flux, which metals and decomposes during the welding operation and forms a kind of protecting shielding layer on the top of the weld bead to protect it from atmospherical oxygen. The SMAW process is famous in industry as it is very cheaper to operate, can weld most of the commonly used metals and alloys and easy to port in harsh environments etc. At the same time there are some limitations associated with the SMAW process such as slag has to be removed and frequent changing of electrodes makes the process slower in nature [13].

Figure 1. Input and output inventory for the SMAW process ([14,15])
2. Establishing framework using triple bottom line methodology
The idea of sustainable development is mainly defined as meeting the needs of current generation without compromising the needs of future generations [16]. Sustainable development plays a key role towards the sustainance of all living ecosystems, as it is not only for the human beings it also includes all living beings in the environment. When analysing sustainability for certain operation, it is important to incorporate all three environmental, economic and social aspects simultaneously. Triple bottom line (TBL) or three pillar of sustainability approach points out at the integration of all three aspects [17–20]. In order to properly address all three components of sustainable development, it is very important to understand the input and output inventory involved in the SMAW process. For the SMAW process the input streams are filler material, electrode and energy consumption. However, the output streams are the final workpiece material, slag and fumes. Figure 2 establishes the TBL based Venn diagram for the SMAW process. Each aspect of TBL sustainability approach is discussed in detail under the light of available literature.

![Figure 2. Triple bottom line (TBL) [21] approach for the SMAW process](image)

3. Discussion
The study provided a framework to characterize sustainability for the most commonly employed welding operation namely SMAW process. Most of the studies available in the state-of-the-art are focused on the technical performance and social aspects of the SMAW operation. However, the presented paper incorporates all social, economic and environmental aspects together by using the fundamental sustainability approach of triple bottom line (TBL). The study is very helpful to see the broader perspective of SMAW process using all three dimensions together as a whole. It can be observed very clearly that the SMAW process has economic advantage over the other welding processes. In addition to the economic gain, SMAW process is also favoured in the industry due to its ease in transportability, which makes its promising for the harsh environments. When environmental impacts of different welding operations were investigated, it has been observed that highest environmental impact was found for manual SMAW process. This reveals the potential of automation in the welding operation. The automated version of arc welding operation can be utilized to reduce the environmental impact of the manual arc welding operation.
The concept of lean manufacturing deals with the minimization of waste throughout the manufacturing process [22]. The result of lean manufacturing based practices generally also results in lowering the environmental burden of the manufacturing process. Similarly, to achieve environment friendly welding operation, implementation of lean practices can be very helpful. Literature reveals [23], [24] some of the lean practices related to the welding operation, such as improving product quality by achieving zero defect, efficient use of all valuable resources, just-in-time material flows, process continuous improvement and introducing flexibility in manufacturing to maximize resource efficiency. In order to extend the discussion, each circle (economic, environmental and social) of TBL approach was further explored in the light of available literature.

3.1 Economic Aspects
It has been reported that annual electricity consumption of welding is $15 million in the US and $99 million globally [22]. Several researchers have focused their work to study the economic aspect of SMAW process. In addition welding operation is a costly process because it involves several types of resources. Performing parametric optimization using different experimental setups would be very expensive solution. Therefore, different approaches including Taguchi method, Genetic Algorithms and other optimizational techniques are very cost effective. Vimal et al. [23] utilized the graph theory approach to model different sustainable measures for the assessment of sustainable strategies. The study incorporated two sustainable strategies of employee skill training and waste reduction. The study revealed that waste reduction through the proposed optimization method bring both economic and environmental benefits. Jármai et al. [24] also conducted a cost optimization study for cylindrical orthogonally stiffened shell member. The study considered the cost function based on the raw materials, forming, welding and painting operations. The study utilized novel mathematical optimizations approaches namely leap-frog – LFOPC, Dynamic-Q, and particle swarm – PSO. The optimal results revealed remarkable margin of material and manufacturing related cost saving by reducing the shell thickness.

Patrick and Newell [25] explored the idea of cost reduction for the arc welding operation. The study revealed different labour and material related costs for the welding operation. It has been observed that costs related to material consumables is only 10 – 20% of overall welding cost, whereas the remaining 80 – 85% cost is related to the labour and overheads. Increase in the productivity can reduce the labour man-hour and decrease the associated cost. Figure 3 represents different deposition rates for various arc welding operations. It can be observed that maximum number of man-hours were reported for the SMAW process. The study suggested to replace SMAW process with another FCAW process to improve overall productivity.

**Figure 3.** Deposition rate for Gas Tungsten Arc Welding (GTAW), Submerged Arc Welding (SAW), Shielded Metal Arc Welding (SMAW) and Flux Cored Arc Welding (FCAW) [25,26]
3.2 Social Aspects
To consider the social aspects related to the SMAW process, it is important to consider the health hazards and risks involved during this operation. Arc welding operation generates fumes with the airborne particle size of 0.1 – 1.0 µm. The welding fumes mainly consist of heavy metals such as chromium (Cr), manganese (Mn), nickel (Ni) and iron (Fe) [27]. Due to the health related hazards, several cases of eye-nose-throat (ENT) infection, chest congestion, bronchitis, pneumonitis, chronic asthma and lungs cancer [28]. Chang et al. [29] conducted a study where different welding processes such as metal arc welding, manual / automatic gas metal arc welding, laser arc hybrid welding, were investigated for their environmental and social impact using life cycle analysis (LCA) approach. The study highlighted that welder salary is fair, but there are serious concerns towards welders own health during the manual welding operation. Higher health risk was reported for manual metal arc welding process. Welding fumes are associated as one of the major risks towards the health of human worker. Slagor et al. [30] investigated the possibility of cataract in the Danish welders by considering the group of 4288 welders. The study revealed that no significant case of cataract was found in the cohort, that means that by using proper safety equipment this possibility can be eradicated. Hexavalent chromium (CrVI) is also present in the welding fumes and it is main cause of lung diseases such as cancer and occupational asthma. Incase if the CrVI is inhaled from the breathing zone of the welder, it can attach the lungs tissue due to its highly reactive nature [31]. It has also been found that during the welding of carbon steel, Manganese (Mn) is released in the welding fumes [32]. Literature has reported the cases of Parkinson and brain damage due to the exposure of Manganese (Mn) [33]. The welding fumes generation rate is mainly based on the chemical composition of the filler material. The percentage of these welding fumes is reported to be around 90 % to 95 %, generated from the filler metal and the flux coating from the electrode material. The generated fumes rate is dependent on the welding rate, welding process, type of coating material, welding Position, welding environment Chromium content and flux ingredients [34]. The literature also points out at the important precautionary measures to reduce the harmful effects of the welding fumes. As per the OSHA occupational exposure limit (OEL) based guidelines, it is important to regularly take the sample of welding fumes and incorporate the sampling head with filter appropriately in the breathing zone of the welder[35,36]. Similarly, it is very important for the factory floor with welding capabilities to have appropriate ventilation facilities. When it comes to the social aspects of welding operation, literature also points out at the salary of the welder as an important parameter. Several studies have been focused to investigate the salary based social aspects. The study performed in the Germany reveals that welder’s salary is sufficient enough to sustain a good quality life [29].

3.3 Environmental Aspects
Due to the generation of hazardous fumes during the welding operation, it is understood that welding operation increases the air pollution. As per the conventional understanding of air pollution, any hazardous particulate or biological molecule that contaminates the natural Earth’s atmosphere is considered as an air pollutant. Reduction of welding fumes can decrease the related air pollution. The literature supports the idea of reducing current intensity to lower the emissions from welding fumes [37]. To improve the environmental performance of the SMAW process, one of the key strategies is to lower the energy consumption in the process. Several researchers have investigated this aspect of the SMAW process. Reduction in the energy consumption of SMAW process, bring several environmental and economic benefits to the overall performance. Sterjovski et al. [38] welded 35 mm steel plates and examined the arc energy heat input for the manual arc welding process. The study investigated the sensitivity and reliability of the parameters required to calculate heat input. The heat input is the measure of total power of arc energy produced to perform a welding of unit length. The study also performed Vickers hardness (HV) and optical microscopy on the welded samples. The results from microstructure and hardness evaluation revealed heat input is linked with cooling rate. Sprousser et al. [15] utilized life cycle analysis (LCA) to compare the environmental impact of different welding processes such as manual metal arc welding (MMAW), gas metal arc welding (GMAW), laser arc hybrid welding (LAHW), spray and modified arc welding processes etc. The study
incorporated welding operations on 20 mm thick structural steel with the weld bead length of 1 m. The LCA study revealed highest environmental impact for the MMAW process as shown in the Figure 4. The advent of modern power electronics has enabled industry to provide more output power as compared to the conventional transformer based sources. For example, inverter based technology can be utilized to replace the old conventional power sources. The modern technology can deliver more efficient and smoother supply of output power [22].

Figure 4. Comparison of environmental impacts for different welding operations [15]

4. Future recommendations and conclusions
The current study characterizes sustainability involved in the SMAW process by using triple bottom line or three pillars of sustainability approach. The study incorporates the available literature to establish the input parameters and output streams involved in the SMAW process. As a result of this current study, several conclusions can be drawn.

- It was found that 80 – 85% of the overall cost in welding operation is related to the labor and other overheads. To maximize the economic gain, different optimization methods can be employed to reduce the resource consumption and cost involved in the SMAW process.
- Fume inhalation by the welder is one of the major health hazards present in the SMAW operation. The risks of this hazard can be significantly reduced by incorporating proper designing and planning of the SMAW process.
The advent of modern power electronics has permitted industry to provide more output power as compared to the conventional transformer based sources. It means that by using modern power electronics there is a huge potential present for the reduction in energy consumption.

It has been observed that there are very limited studies available in the literature where life cycle analysis (LCA) of a welding operation has been performed. Further studies can be performed to implement LCA for welding operations.

The study observed that very limited literature is available in the area of numerical modeling of a welding operations. As future recommendation, more studies can be performed to develop more precise numerical models based on the coupling of Multiphysics such as heat transfer, fluid flow and electromagnetics.

As the welding process involves solidification and melting of metal, it is important to capture the proper physic and phase change in the numerical model to attain accurate performance predictions.

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