# SUSTAINABILITY ASSESSMENT OF WELDING PROCESSES

by

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# Abstract

In today's world, calls for 'sustainability' are increasing in order to preserve our resources and our environment. Many initiatives are being put in motion to make our lives more 'sustainable'. This concept of 'sustainability' has recently risen to take the old concept of going 'green' further. To elaborate, where 'green' aimed to preserve the environment and decrease the emissions of greenhouse gases and other harmful substances, 'sustainability' takes the economy and society into consideration. This is done by considering how much money it would cost, how it would affect the society, and how to be more environmentally friendly for a particular product or process. This thesis aims to outline general methodologies for sustainability assessments. This would then be adapted for manufacturing processes, and then would be applied to measure and assess the sustainability of welding processes. The objective is to build a complete framework that would be used to determine the best welding process for a particular application. To apply this methodology, data about the welding processes was collected and segregated into four categories: environmental impact, economic impact, social impact, and physical performance. Each of these categories had a number of indicators which would quantify the performance of each process. This quantification step was done by developing specific equations and applying them to the indicators. An aggregate sustainability score was then obtained from the individual scores of each category. However, to avoid taking the arithmetic average which indicates equal importance for each category, a weighted average was suggested in this thesis. To obtain the respective weights, a survey was created and distributed to experts. The collected results were analyzed and incorporated to calculate the aggregate score. To demonstrate the capability of this methodology, three welding processes, gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), and friction stir welding (FSW) were assessed on welding Aluminum 5083. This would determine the most sustainable process in that particular application. The final outcome showed that FSW was the most sustainable process for the application.

**Search Terms:** Sustainability, assessment, welding, Shielded metal arc welding, Gas metal arc welding, and Friction stir welding

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| | |
|---|---|
| BLS | Bureau of Labor Statistics |
| FSW | Friction stir welding |
| GMAW | Gas metal arc welding |
| GTAW | Gas tungsten arc welding |
| MSDS | Material Safety Data Sheet |
| SMEs | Small and Medium Enterprises |

# Chapter 1. Introduction

Global climate change poses the greatest potential threat to mankind today. In addition to that, its implications pose the greatest challenge due to the amount of effort required to mitigate the problem. Climate change might be irreversible for about 1,000 years after total emission halt. This means that the assumption that climate change poses little risk, and that measures taken any time would reduce emissions within a few decades are incorrect. This happens because even with the removal of atmospheric carbon dioxide, atmospheric temperatures would not drop significantly due to the slow heat loss to the ocean. Moreover, sea level rise, increased acidification of the ocean, and rainfall reduction are the other observable results of global warming and emissions. Various scenarios predict the rise of carbon dioxide concentrations from the current levels of about 385ppmv to a peak of 450-600ppmv over the present century which could result in a temperature rise of 1.4-5.88 °C, and a sea level rise of 0.4-1.0m. For comparison, there has been anthropogenic global warming of 0.58 °C over the past century. Some of the mitigation measures that could be taken are [1]:

1. Saving energy and developing new and efficient technologies
2. Having cleaner technologies for electricity generation
3. Reducing transportation sector emissions
4. Developing renewable sources of energy
5. Getting ready for the indispensable adaptation to future challenges in the climate system

In 1992, Energy Star was introduced by the US Environmental Protection Agency (EPA) as a program designed to identify and promote energy-efficient products to reduce greenhouse gas emissions, starting with computers and monitors. Through 1995, Energy Star was expanded to additional office equipment products, residential heating, and cooling equipment.

Through its partnerships, Energy Star delivers the technical information and tools that organizations and consumers need to use in order to be more energy-efficient. Energy Star has successfully contributed to energy and cost savings across the US of nearly $24 billion in 2012 alone [2].

International and national efforts to monitor and reduce the carbon footprint have been done in the past two decades. Negotiations have not yet yielded global agreement and implementation. Among the various disagreements, the disparity in the perspective of the importance of emissions versus economic growth expected over the next few decades between developed and rapidly developing countries has created dissimilar incentives [3]. Developing countries favor investing their funds in the development of more environmentally friendly initiatives. On the other hand, less developed countries prefer that their funds go to raising the economy within the country through creating new jobs, or increasing the efficiency of the existing financial systems. This became a bigger issue after the global financial crises of 2007/2008 and 2014/2015.

The financial crisis of 2008 has impacted economy across the world. The crisis that originated in developed countries, affected the developing economies in a great number of ways. The fall in import of developed nations from developing countries, and the decline of commodity prices resulted in less export earnings. Consequently, the economy of developing countries was devastated. Countries which depended on primary and processed products were hit hard. In addition to that, countries like India and China that are exporters of skill commodities, such as computer software, are facing serious problems due to decreased demand in lower prices for these products [4].

The sharply falling rates of economic growth, massive job losses, and increasing poverty are all shaking the economic foundation of the global economy. Developed countries have desperately fallen back upon monetary and fiscal measures for getting out of the crises [4].

In order to meet the needs of both the developed and developing countries, a new tool must be developed to help all countries and economies make the best decisions when it comes to all problematic aspects:

- Performance
- Economy
- Environment
- Society

## 1.1. Sustainability

The most widely accepted general definition of sustainable development is provided by the United Nations' Brundtland Commission: 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' [5]. This development has seen particular impact on the manufacturing field. Recently, there has been increased pressure on manufacturing companies to think beyond the economic benefits of their processes and products, and to consider the environmental and social effects as well. This has made manufacturers promote processes and products that minimize environmental impact while maintaining social and economic benefits. This notion has been taken up by many consumers, who wish that their products be created in a sustainable manner. This situation has challenged manufacturing enterprises around the world to stay competitive in the market place by developing and implementing sustainable manufacturing techniques and tools [6]. The need for sustainability in industrial processes is increasing these days due to various factors such as:

- Decrease in the amount of non-renewable resources available
- Increase of regulations on industrial process waste and emissions
- Increased safety requirements
- Increase in the demand for efficiency

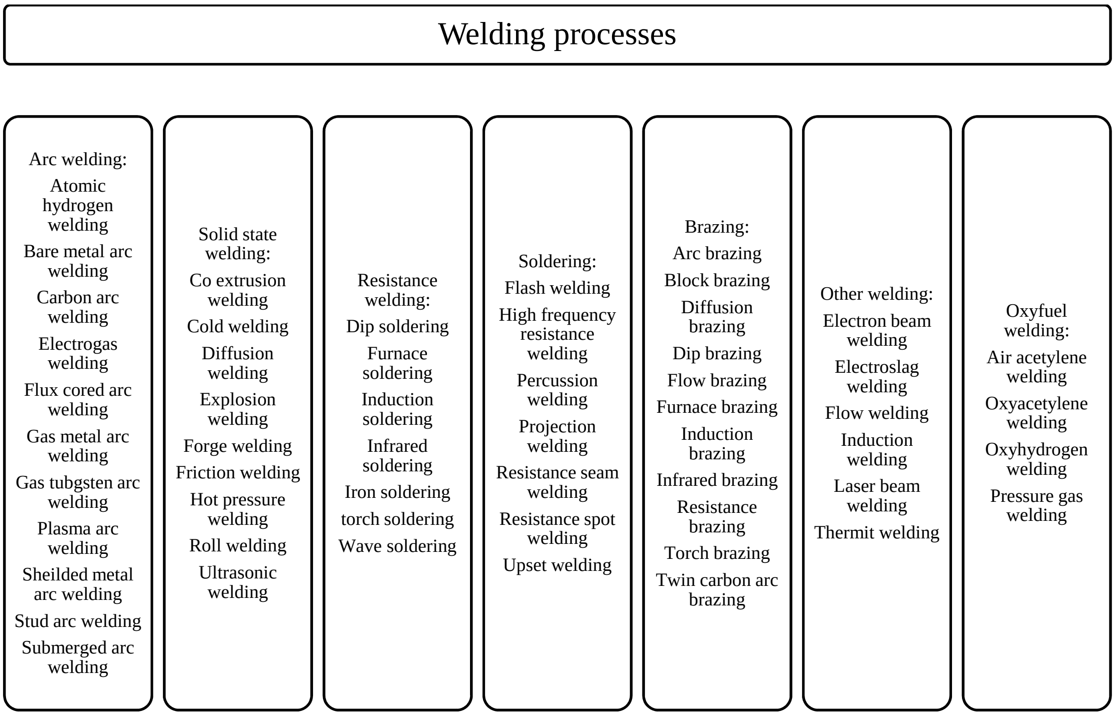
Sustainable manufacturing is defined by The U.S. Department of Commerce as: 'the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound' [5]. Ideal sustainable manufacturing would be the development of processes where no greenhouse gases are emitted, only renewable materials are used, and no waste is generated [6]. Julian Allwood [6] suggests five methods in which sustainable manufacturing may be approached:

1. Increasing the efficiency of manufacturing, which could lead to the decreased use of raw material and energy
2. Substituting any non-sustainable input material for sustainable ones, such as renewable sources of energy rather than conventional sources
3. Coming up with methods that decrease or even eliminate manufacturing waste
4. Increasing the usage of waste through recycling and reuse
5. Developing better supply chain management structures

From the definition, it can be concluded that the concept of sustainability of a particular product or process studies the environmental effects, cost and society as well as the physical performance of the product. With the inclusion of society and economy to the environmental aspect, this novel concept is an improvement on the concept of being ‘green’ or ‘environmentally friendly’ [6].

## 1.2. Welding

Welding is one of the most important processes in the manufacturing sector. It is essentially the process of joining of two or more objects for the purpose of assembly. There are various welding techniques and processes to join materials, and the choice is usually made based on the type of material, quantity and size of the product. Figure 1 shows the different types of welding processes:



Welding processes

Arc welding:
- Atomic hydrogen welding
- Bare metal arc welding
- Carbon arc welding
- Electrogas welding
- Flux cored arc welding
- Gas metal arc welding
- Gas tubgsten arc welding
- Plasma arc welding
- Sheilded metal arc welding
- Stud arc welding
- Submerged arc welding

Solid state welding:
- Co extrusion welding
- Cold welding
- Diffusion welding
- Explosion welding
- Forge welding
- Friction welding
- Hot pressure welding
- Roll welding
- Ultrasonic welding

Resistance welding:
- Dip soldering
- Furnace soldering
- Induction soldering
- Infrared soldering
- Iron soldering
- torch soldering
- Wave soldering

Soldering:
- Flash welding
- High frequency resistance welding
- Percussion welding
- Projection welding
- Resistance seam welding
- Resistance spot welding
- Upset welding

Brazing:
- Arc brazing
- Block brazing
- Diffusion brazing
- Dip brazing
- Flow brazing
- Furnace brazing
- Induction brazing
- Infrared brazing
- Resistance brazing
- Torch brazing
- Twin carbon arc brazing

Other welding:
- Electron beam welding
- Electroslag welding
- Flow welding
- Induction welding
- Laser beam welding
- Thermit welding

Oxyfuel welding:
- Air acetylene welding
- Oxyacetylene welding
- Oxyhydrogen welding
- Pressure gas welding

Figure 1: Various welding processes [7]

In 1885, Elihu Thomson started the development of resistance welding. This continued over the span of the next 15 years. Later in 1989 thermite welding and oxyfuel welding were invented and became well established. At the time of its invention, oxyfuel welding rose to become one of the more popular welding processes owing to its portability and relatively low cost. As the 20th century progressed, however, it fell out of favor for industrial applications with the rise of arc welding processes. Arc welding electrodes were being coated with metal coverings, known as flux, that stabilize the arc and shield the base material from impurities producing better quality welds [8].

The development of welding processes continued. This led to the introduction of automatic welding in 1920, in which electrode wire was fed continuously. Moreover, shielding gas became a subject receiving much attention, as scientists attempted to protect welds from the effects of oxygen and nitrogen in the atmosphere to yield better weld properties. Porosity and brittleness were among the major causes. Among the solutions that were developed was the use of hydrogen, argon, and helium as temporary welding atmospheres. The following advancement sought to create processes for the welding of reactive metals like aluminum and magnesium [8].

As a result of the mentioned development of all welding processes, various processes that are used today were invented in the mid-20th century. In 1930, Kyle Taylor developed stud welding, which is used in shipbuilding and construction. Submerged arc welding was also invented that year. After decades of development, gas tungsten arc welding was introduced in 1941, and gas metal arc welding followed in 1948. This allowed for fast welding of non-ferrous materials. The disadvantage was that expensive shielding gases were required. This led to the development of shielded metal arc welding during the 1950s. In 1957, the flux-cored arc welding was invented to create self-shielded wire electrodes that could be equipped to automatic equipment. In addition to that, plasma arc welding was invented later that year. Electro slag welding was introduced in 1958, and it was followed by electro gas welding, in 1961 [8].

More recently, developments in welding included the development of electron beam welding in 1958, which made deep and narrow welding possible through the concentrated heat source. After the invention of the laser in 1960, laser beam welding followed, and has been useful in high-speed, automated welding. Later, magnetic pulse welding was developed in 1967. In 1991, Friction stir welding was invented by Wayne Thomas at The Welding Institute for the welding of reactive, soft metals such as Aluminum [9]. Joining of aluminum parts has been a problem in the manufacturing business as conventional welding techniques do not provide proper results. Solidification of aluminum after welding leaves a porous microstructure in the fusion zone. This creates a significant loss in mechanical properties. FSW requires a specially designed tool that rotates and translates along the joint of two parts. Heat for bonding is created by the friction between the rotating tool and the surface of the joint. The tool then traverses the length of the joint to complete the weld. FSW is considered to be green because it uses less energy and it does not require cover gas or flux [10].

Welding is a very critical step in the assembly because if not done properly, it may result in stress concentrations which would weaken the entire assembly. These stress concentrations may develop due to various reasons, some of which are listed [11]:

1. Imperfections formed while the weld cools
2. Oxidization of the weld if not protected from the atmosphere
3. Grain characteristics change near the weld areas due to the immense heat (Heat Affected Zone)

Electrical power is predominantly the main source of energy input for the most welding processes. This energy is used to fuse the filler metal with the base metal. To prevent the oxidation of the weld through contact with the atmosphere, shielding methods are typically used. These methods vary for each process. Some of the more predominant processes are listed in Table 1 with some of their main characteristics:

Table 1: Few welding process details

| Process | Usage | Shielding method |
|---|---|---|
| Shielded Metal Arc Welding (SMAW) | Manual, carbon steel | Layer of slag |
| Gas Metal Arc Welding (GMAW) | Manual, carbon steel | Inert gas (Argon) |
| Flux Core Arc Welding (FCAW) | Manual, Nickel Alloy | Flux |
| Submerged Arc Welding (SAW) | Automated, carbon steel | Flux |
| Friction Stir Welding (FSW) | Automated, Aluminum/Magnesium | N/A |

Due to the immense amount of heat generated during the welding and the various harmful emissions, welding is considered to be a dangerous activity. Special training must be given to all welders before starting their jobs. In addition to that, welder training must be renewed periodically. These hazards, in addition to some others, are mentioned below [12]:

- Electrical Safety and Magnetic Fields

Due to the potential severity of the consequence of the hazard, some safety precautions could be taken to prevent potential accidents related to electrical hazards:

  - Only qualified personnel should be allowed to install welding equipment.
  - The equipment must be tested to ensure it is operating correctly and safely before being put into service.
  - Welders should not remove panels from a welding power source if it stops working correctly.
  - Never ignore a blown fuse; it is a warning that something is wrong.
  - When welding is temporarily interrupted welding guns should be placed where they are safe and the gun switch cannot be activated accidentally.

- Compressed Gases

Shielding gases used for welding may be inert, active, or a mixture of inert and active gases. Some precautions that could be taken:

  - Always use the correct regulator for the gas, suitable for the pressure in the cylinder.
  - Don’t modify a regulator for another product.

- Heat

During welding, any source of heat, which includes welded components, the electrode holder and hot electrodes can cause burns. In confined spaces, a hot environment would be formed.

- Welding Fume and Gases

Welding fumes are unavoidable as welding by-products. Welders should be aware of what fumes are likely to be emitted during welding. Particulate fumes are formed from the vaporization of welding consumables. These are usually metal oxides from the filler and the base metal. Arc welding processes are also likely to form gaseous fumes from the reactions between ultraviolet light and heat on atmospheric oxygen and nitrogen.

- Noise

Welding generates noise. Power sources generate high frequency noise.

- Manual Handling

Back injuries are considered one of the most common industrial injuries suffered by workers. Welders in particular suffer from them because of awkward welding position in confined spaces, especially when carrying consumables and other welding equipment.

- Confined Spaces

Confined spaces amplify the criticality of the existing hazard. This is mainly due to decreasing the volume which inherently increases concentrations.

- Solvents

Flammable solvents may be used to clean components prior to welding and may still be residing in the welding area. This is a fire hazard which needs to be taken seriously in pre-weld inspections.

## 1.3. Literature Review

**1.3.1. General framework for sustainability studies.** With the rise of the need for sustainable manufacturing processes and products, a need for a standardized methodology or framework for the quantification and assessment of sustainability performance grew. Unfortunately, no generalized assessment criteria have been established and this really creates inconsistency and bias when comparing manufacturing processes and techniques. A great number of indicator sets and indices have been published to try and tackle this issue [13].

More than eleven indicator sets have been developed to analyze and assess the sustainability performance of manufacturing processes. Since the field of sustainability assessment is very wide and relatively new, another method for assessing sustainability has been introduced. This has been done by means of indicators, indices, and frameworks for analyzing sustainable manufacturing. The existence of the great number of indicator sets has created confusion among manufacturers when attempting to select a set of indicators for assessing sustainability. Moreover, Gaurav et al. [14] state that major sustainability metrics are inconsistently defined and largely business-specific. For example, the Organization for Economic Cooperation and Development (OECD) Core Environmental Indicators (CEI) includes 46 indicators used to measure the impact of industrial activities on the environment in industrialized countries. On the other hand, the United Nations (UN) Commission on Sustainable Development identifies 96 indicators to address environmental issues [13].

In contrast to indicator sets, indices provide a more direct result of sustainability performance because they rely on weight-based mathematical equations to aggregate many indicators into a single score. By analyzing the single score, a sustainability level can be set and used as a metric for performance. Comparing and improving sustainability performance still remains problematic due to contrary opinions on the compositions and interpretations of the indicators of an index. This leads organizations to develop a number of indicators, sets, and indices in an attempt to match the various levels of decision making for sustainability [13].

To further address this issue, the National Institute of Standards and Technology (NIST) has developed a categorization of sustainability indicators that classifies a large number of indicators into appropriate categories and subcategories. The categorization provides a holistic structure to integrate all the possible indicators from which companies can choose to assess sustainability for their products and processes associated with manufacturing [13].

According to the National Institute of Standardization and Technology's (NIST) categorization to group indicators, there are five main categories:

1. Environmental stewardship
2. Economic growth
3. Social well-being
4. Performance measurement
5. Technological advancement indicators

It has been suggested by C.B. Joung et al. [13] that it would be easier to interpret sustainability performance that would be a result of a mathematical formula. This formula would be developed after choosing the appropriate indicators and group them in the relevant category. To choose the indicators, the authors proposed steps to determine and select the indicators for these categories:

1. Setting an objective; this is the objective for which the study is being carried out

2. Selecting indicators; these must be chosen appropriately such that they can effectively provide measurement that would help quantify the problems in a particular process and product. This step is very subjective and therefore requires experts to be able to make the appropriate choice
3. Specifying performance; this is the determination of the required level to be reached by the indicator
4. Specifying measurement procedure
5. Analyzing the data collected
6. Providing a report
7. Making a managerial decision; this could determine the action to be taken and the severity of the action
8. Evaluating the outcome

After the selection of the indicators from existing sets, the authors have decided to evaluate them before finalizing their usage. For evaluation, the authors chose to access the indicator sets by:

1. Measurability
2. Relevance
3. Understandability
4. Reliability
5. Data accessibility
6. Periodic collection of data
7. Long term availability

Danfang Chen et al. [15] have suggested that following sustainability assessment for development planning for small and medium businesses (SMEs) is the best guideline to follow. The authors have begun by studying various assessment methods and have compared their characteristics in relevance to the assessment of SMEs. Their conclusions are shown in Table 2:

The assessment tools which have been found to be lacking have been explained by the authors. They have found various shortcomings with these methods and have summarized them in the following points [15]:

- Missing holistic focus of sustainability

- Lacking applicability to companies from other industrial branches or barely comparable assessment results
- Time consuming assessment due to the complexity and amount of data required
- Lack of applicability on the factory level

Table 2: Evaluation of various sustainability indices [15]

| Indices | Rapid assessment | Application on factory level | Generic applicability | Holistic view of sustainability |
|---|---|---|---|---|
| Barometer of sustainability | Yes | No | Partial | No |
| Dow Jones sustainability index | No | Yes | Partial | Partial |
| GRI reporting framework | No | Yes | Partial | Yes |
| IChemE sustainability metrics | No | Yes | No | Yes |
| Rapid plant assessment tool | Yes | Yes | Partial | No |
| Sustainability assessment in mining and minerals | No | Partial | No | Yes |
| Composite sustainable development index | Yes | Yes | Partial | Yes |
| ITT Flygt sustainability index | Yes | Yes | No | Yes |
| Ford of Europe’s product sustainability index | No | No | No | Yes |
| GM metrics for sustainable manufacturing | Yes | Yes | No | Yes |
| Sustainable consumption and production framework | No | No | Partial | Yes |
| Rapid Basin-wide hydropower sustainability assessment tool | Yes | No | No | Yes |

Singh et al. [16] aimed to give an overview of various sustainability assessment strategies. However, they start by stating that a holistic approach does not exist, but it would be worthwhile to define a set of indicators to measure the sustainability performance of countries and companies. The main difficulty lies in aggregating these different indicators with different dimensions into a single sustainability score.

For the evaluation of given sustainability indicators, the authors followed Booysen's [17] approach. These are the criteria on which the indicators and indices would be chosen and judged:

- Aspects of the sustainability to be measured by indicators.
- Techniques/methods/tools used for the development of index.
- Whether the indicator compares the sustainability measure across, absolute or relative manner.
- Whether the indicator measures sustainability in terms of input or output.
- Clarity and simplicity in its content, purpose, method.
- Availability of data for the various indicators.
- Flexibility in the indicator for allowing change.

After a thorough analysis of methodologies assessed in the paper by Booysen [17], it can be concluded that none of the available indices provide a complete approach to measure sustainability for all processes, products, corporations, etc. because ultimately all indices are subjective and cannot be applied universally. Instead of attempting to develop sustainability indices to be applied to everything, efforts should be concentrated to develop a sustainability index for each aspect for the sake of standardizing its use.

Tomas et al. [18] have set up another framework to evaluate various sustainability indicators aimed at revising and updating assessment methodologies. They state that indicators must:

- Evaluate all assessed activities
- Be appropriate for assessing the application
- Provide a measurement for the sustainability

The authors also state that in order to evaluate a process or a system fully, four principle areas must be considered when selecting indicators:

- Planning and design
- Data collection and processing
- Presentation and results
- Updates and reviews

In their proposed evaluation methodology, the authors have assessed the complete sustainability assessment index, and have evaluated each of the indicators used. During the evaluation, the authors proposed the use of a three point raking system to quantify the indicator performance. These points may then be aggregated into a single score. Through the analysis of the score of the indicators, the user would get a general overview of the performance of the particular index. In case the performance score is lower than expected, the affecting indicator could be identified and amended.

Booysen [17] has focused his research on developing measuring indicators and their evaluation. He summarized his evaluation strategy criteria in Table 3. The methodology followed defined steps which led to the development of his strategy. First, the main objective was defined with the categories which are needed to achieve the main objective. The categories defined were economic, social and political development. Then, the literature was consulted to obtain the indicators for each category. For the selection of these indicators, the indicators must:

- Meet the objective
- Be measurable
- Be reliable
- Be simple
- Be specific

Table 3: Indicator evaluation criteria [17]

| Dimension | Description |
|---|---|
| Content | What aspects of development does the indicator measure? |
| Technique and method | Is the measurement qualitative, quantitative, ordinal, or multidimensional? |
| Comparative application | Is the comparison for a cross section/time period, or absolute/relative? |
| Focus | Is the measurement done in terms of input or output? |
| Clarity and simplicity | How clear is the indicator for the purpose? |
| Availability | Is the data readily available for the indicator? |
| Flexibility | How flexible is the indicator for changes in the method? |

After defining the indicators, scaling was done to make sure that all the indicators are comparable before aggregation. Finally, the indicator and category scores would be aggregated and validated. The author then applied his methodology to various existing sustainability indices identifying their strengths and shortcomings. The findings are summarized in Table 4:

Table 4: Evaluation of dimensions for various sustainability indices [17]

| Description | Demographic | Education | Health | Infrastructure | Political stability | Culture | Environment | Civil institutions | Income | Unemployment | Poverty | Economic freedom |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Combined consumption level index | Yes | Yes | Yes | Yes | No | Yes | Yes | No | No | No | Yes | No |
| Human resource development index | No | Yes | No | No | No | No | No | No | No | No | No | No |
| Real index of consumption | No | No | Yes | No | No | No | No | No | No | No | No | Yes |
| General index of development | Yes | Yes | Yes | Yes | No | No | No | No | No | Yes | Yes | Yes |
| Physical quality of life index | Yes | Yes | Yes | No | No | No | No | No | No | No | No | No |
| Composite basic needs indices | Yes | Yes | Yes | No | No | No | No | No | Yes | No | No | No |
| Index of social progress | Yes | Yes | Yes | Yes | Yes | Yes | No | Yes | Yes | No | Yes | No |
| World standard distance scales | Yes | No | No | Yes | No | No | No | No | Yes | No | No | No |
| Human suffering index | Yes | Yes | Yes | Yes | No | No | No | Yes | Yes | Yes | No | No |
| Quality of life ranking | Yes | Yes | Yes | Yes | Yes | No | No | Yes | Yes | Yes | No | No |

1.**3.2. Sustainability indices.** Standardized sustainability indices and metrics have been published and their use is reliable for their specific supplication. The choice of which index to follow is a very critical process because the one chosen must be relevant to the process/product being assessed. Otherwise, one or more aspects of a process or product would most likely be overlooked. This could result in an incomplete study, and the whole study would be deemed questionable. Some of these are:

1. Global Reporting Initiative
2. Dow Jones Sustainability Index

3. General motors sustainability index
4. Organization for Economic Co-operation and Development
5. Ford's Product Sustainability Index
6. EU Eco-Management and Audit Scheme EMAS

The Global Reporting Initiative (GRI) [19] standards represent the best sustainability reporting practices for worldwide organizations. The data collected is split into 3 main categories:

- Economic
- Environmental
- Social

Companies worldwide are using the GRI to report their sustainability performance through a specified set of indicators related to each category. They provide many publications to help organizations report their performance as correctly and accurately as possible [19].

General Motors [20] stated to have standardized their sustainability assessment index. It is aimed the index at manufacturing companies, but it claimed that it can be used for any firm. General Motors [20] aimed to follow the following guidelines which are believed to be required for all indices:

- Address all needs of the stakeholders
- Facilitate growth
- Harmonize local, state, national, and international levels of business units and operations
- Be fully compatible with existing business systems
- Measure what needs to be measured

General Motors [20] then stated the process which for the development of all indices. To build their sustainability index, these steps were followed:

1. Creating a list of “reference metrics” through examining what peer organizations are using. Deducing what is measurable in order to use any of these metrics
2. Considering additional metrics stakeholders who are likely to care about, and discuss the metrics with them

3. Providing proposed metrics for each level for evaluation
4. Evaluating all the proposed metrics and ascertaining a list that evaluates all major aspects of sustainability
5. Re-checking the edited list for completeness and coherence
6. Determining what should be measured, and how the measurement would be done in order to be able to have consistent, meaningful numbers on each metric
7. Determining how to normalize the measured metrics to remove dimensions from the index
8. Setting achievable goals for each metric and milestone path to achieve them.
9. Passing the information and education of sustainability to all employees. This helps in explaining the new vison of the company, and creating a new mindset for all employees.

GM then added to this list a few more steps from their side. This is to be used specifically for GM sustainability measurement, and other firms may use them to improve their indices as required:

Metrics at different levels should be:

1. Consistent with the level of abstraction from operational detail relative to the particular level of the firm [20]:
    a. Coherent at the different company levels, so as to push the entire company toward common objectives
    b. Interconnected, so as to check each other out and encourage companywide adoption
    c. Systematic measurement should monitor progress and quantify improvement, savings, efficiency gains, etc.
2. Measurement should be complemented by regular and irregular audit, and by internal and third party independent auditors
3. Metrics and goals should be set following accepted third party or industry-wide practices, to allow meaningful benchmarking and gain credibility
4. Cross-flow of information is fundamental to spread the progress across the company’s operations, across geographies, divisions and sub-divisions, subsidiaries, groups, etc.

5. Independent certification and auditing would give the entire process added credibility to the outside

After a study of the literature done by researchers, GM conclude their paper by summarizing their index in Figure 2 which highlights the indicators they have chosen to go with each category:

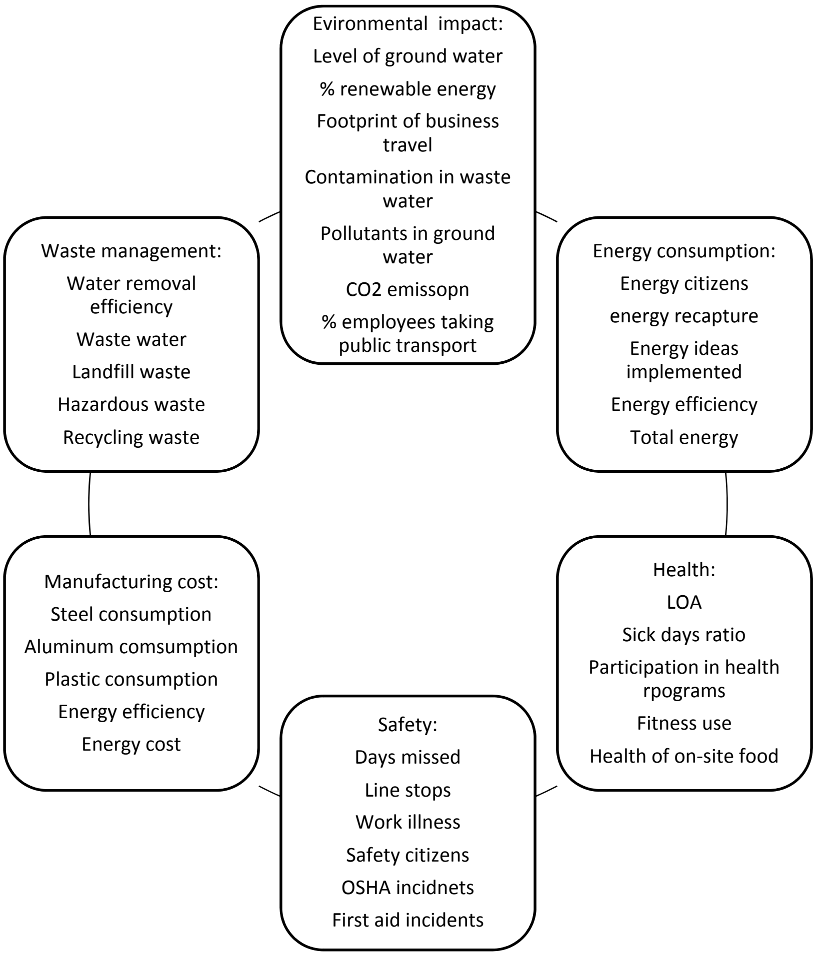


Figure 2: GM sustainability index categories and indicators [20]

The EU EMAS [21] have developed their own sustainability index with a focus in environmental indicators. Their approach is based on three categories and is summarized below:

Operational performance indicators (OPIs): These concentrate on the aspects associated with an organization’s operations including activities, products or services.

Management Performance Indicators (MPIs): These concentrate on the efforts of management to provide the infrastructure for environmental management to succeed.

Environmental Condition Indicators (ECIs): These give information on the quality of the environment surrounding the organization or the local, regional or global state of the environment.

These three categories of environmental indicators have become widely accepted. Organizations should consider a combination of these indicators in order to be able to demonstrate that [21]:

- They understand the environmental impacts associated with their activities, products and services (ECIs)
- They are taking appropriate measures to ensure the management of environmental aspects associated with the environmental impacts (MPIs)
- The results of the management of environmental aspects have improved environmental performance of their operations (OPIs)

The Dow Jones Sustainability Index (DJSI) is used to assess companies. It is used by investors to pinpoint the best companies in 3 main categories:

1. Environment
2. Economy
3. Social

The assessment relies on distributing a survey to a great variety of companies from each sector. The companies which respond complete the survey themselves. Others which do not respond have the survey completed for them by the surveying entity based on public available information. The survey and the scoring structure is reviewed and evaluated each year. The highest performing company is set as the benchmark and the highest possible outcome, and then the others are given an appropriate score with the benchmark being the highest possible value. [22]

The Ford Product Sustainability Index (FPSI) [23] was developed by Ford for the European market, where the need for sustainable products is growing. The principles defining what had to be covered by the FPSI were management and methodologically driven [23]:

- All relevant environmental, social, and economic issues have to be addressed
- Only issues that are mainly influenced by Product Development would be dealt with
- The main issues must be integrated from a product perspective

- Status-tracking must be possible based on readily available product development data
- Bottom-line issues must be addressed, not single technologies (i.e. overall Life Cycle performance, not discussions of the use of certain, specific technologies)
- Business principles must be integrated

The FPSI is concluded by explaining that there is no reasonable way to combine aspects as diverse as safety, use of recycled materials, and cost into one number. This would require, for example, a socially acceptable weighting of their relative importance. Global companies with global markets face the challenge of being confronted by differing values in their various markets and production locations. A single weighting of the relative importance would never be universally suitable for all regions. The findings of Ford Europe are summarized in Table 5:

Table 5: FPSI categories and indicators [23]

| Category | Indicator | Method |
|---|---|---|
| Environmental and health | Life cycle global warming | Greenhouse emissions |
| | Life cycle air quality | Summer Smog |
| | Sustainable materials | Recycled and natural materials |
| | Substance management | Vehicle interior air quality |
| | Drive-by-noise | Exterior noise |
| Societal | Safety | EuroNCAP stars |
| | Mobility capability | Seats and luggage size compare to vehicle size |
| Economics | Life cycle cost | Sum of vehicle and 3 years’ service |

**1.3.3. Sustainability studies performed.** With the increasing need for sustainability to become the ultimate decision making tool, researchers have started publishing papers to tackle a wide variety of topics. These researchers would like to change the perception of problem solving and the decision making process by developing methodologies to assess sustainability. These are then introduced as the best decision making tools. Some of these will be discussed in this section.

A comparison of three different economies was used as an example to assess the validity of four metrics by D.P. Sekulic et al [24]. They focused on the energy area of sustainability and called for the use of more complicated indicators as energy usage does not give an indication of efficiency. Instead, the authors called for the use of exergy. Moreover, to draw a different picture of sustainability, the authors chose indicators which can be correlated. These are:

1. Exergy, as an economic impact indicator
2. GDP, as a social impact indicator
3. HDI, as an economic impact indicator
4. CO2 footprint, as an environmental measurement.

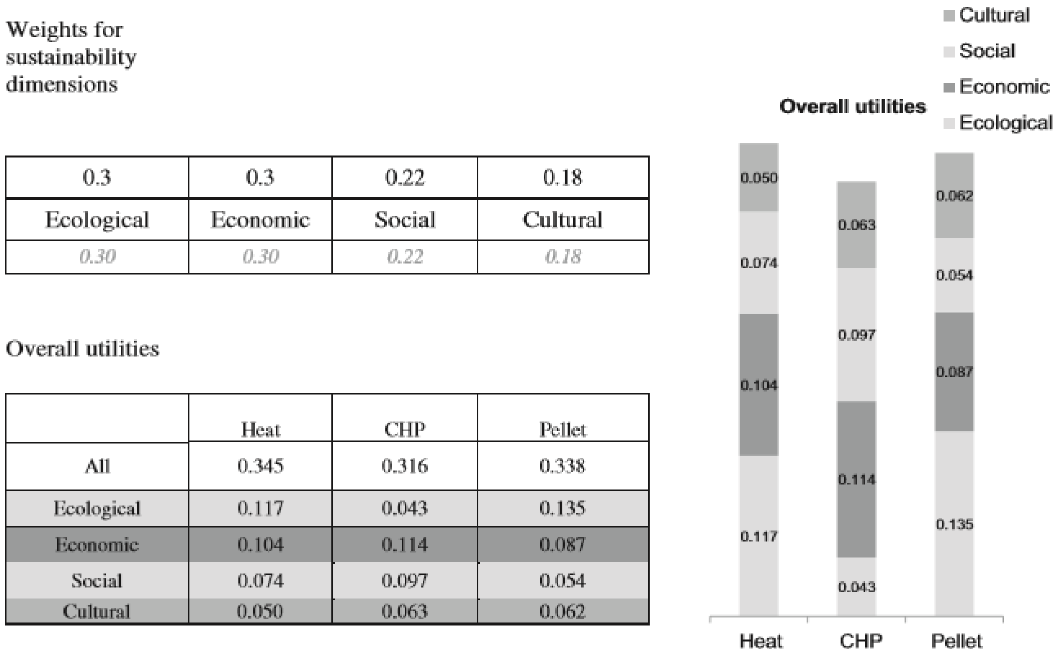
These four were all plotted at a single time to assess the change in each one of them. A compound sustainability metric was defined, but a clear function was not established. Instead, the authors have given the positive trend of the change of each of the metrics with respect to time [24].

The sustainability assessment of bioenergy from wood has been studied by Tanja et al [25]. They state that sustainability assessment as a general methodology is measured through indicators. Since there is no consensus on how to use the indicators, data is usually missed or not reported properly. They have chosen the following categories for their study from their literature review:

- Economic
- Ecological
- Social
- Cultural

The indicators were all scaled and then added together to achieve a single category score for each category. However, in order to adjust the category scores based on the importance, the researchers issued a survey to the North Karelia Forest Council, which a legal body created by the ministry of agriculture and forestry in Karelia. The results of the survey were analyzed to obtain the respective weightages. Next, the weights were multiplied with the category scores to get the corrected scores.

The authors plotted the sustainability assessment results on a bar chart with the category scores added on top of each other. The highest bar would represent the most sustainable process as shown in Figure 3, however, the actual scores were not added to give an aggregate score.



Weights for sustainability dimensions

| 0.3 | 0.3 | 0.22 | 0.18 |
|---|---|---|---|
| Ecological | Economic | Social | Cultural |
| *0.30* | *0.30* | *0.22* | *0.18* |

Overall utilities

| | Heat | CHP | Pellet |
|---|---|---|---|
| All | 0.345 | 0.316 | 0.338 |
| Ecological | 0.117 | 0.043 | 0.135 |
| Economic | 0.104 | 0.114 | 0.087 |
| Social | 0.074 | 0.097 | 0.054 |
| Cultural | 0.050 | 0.063 | 0.062 |

Figure 3: Bioenergy sustainability case study results [25]

Alyami et al. [26] attempted to develop a sustainability assessment methodology for buildings in KSA. LEED and BREEAM are not adapted to consider the specifics of politics, environment, and society in KSA. Therefore, the authors chose to develop a new assessment methodology as their objective using the ranking Delphi technique.

First the Delphi panel is selected by experts, and the size of the panel should lie between ten and fifty. These experts must have the capability, knowledge and relevant experience to be applicable for inclusion. The authors gathered thirty three experts using the following criteria:

- Academic specialist in the area of Sustainable Development
- Decision-maker, manager, or practitioner in the field of sustainable and green building
- Accredited professional in one of the leading sustainable assessment systems
- Practical experience and sufficient knowledge of the sustainable development potential within the KSA.
- Expert with a level of influence regarding the adoption of the resulting methodology

- Willingness to participate

The selected indicators have been illustrated by the authors in Figure 4:

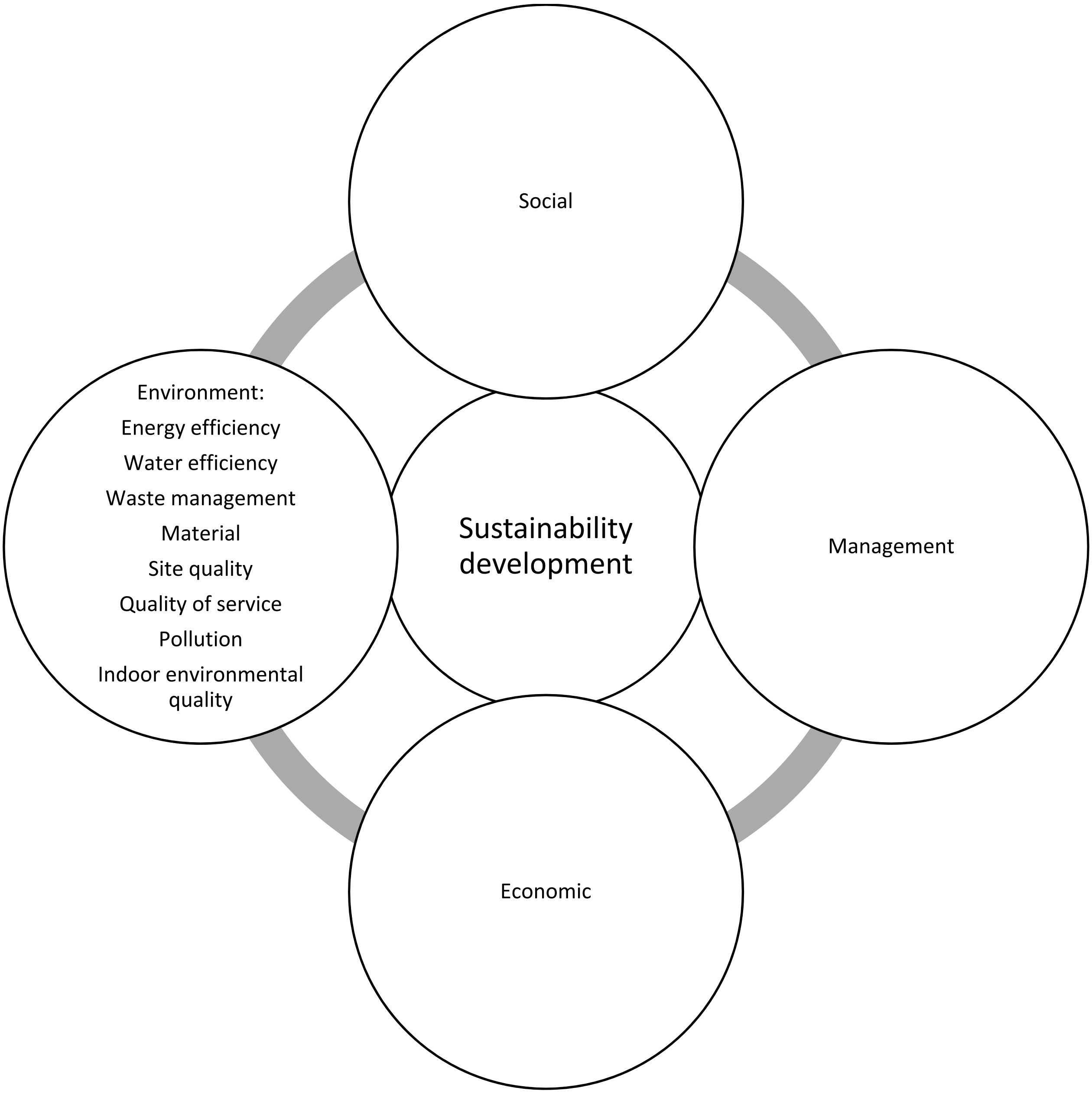


Figure 4: Sustainable buildings assessment methodology [26]

**1.3.4. Sustainability studies on manufacturing processes.** Sustainability studies have also been applied to various manufacturing and industrial applications. As mentioned, they aim to assist the community in making better decisions when choosing different designs, products, processes, etc. Some of these studies are discussed in this section.

Mohammad Ordouei et al. [27] have run a sustainability study on a few gasoline blends. In order to study these blends, the authors have chosen a set of criteria to assess the blends:

1. Octane number: This would measure the quality of the fuel. The higher this number, the better
2. Heat value and mileage: This would provide a measurement on the efficiency of the fuel
3. Price: This would be used to measure the economy of the product
4. Environmental impact: This might be measured by the emissions, and then could be used to tell which of the fuels is more environmentally friendly.
5. Safety risk: This was measured by a formula specific to chemical processes. This is used to assess the safety risk associated with manufacturing the fuels.

The authors then employed the Analytic Hierarchy Process in order to perform as assessment based on several criteria. This method requires the user to provide the ranking which the user feels is appropriate. The highest and lowest values in the study are taken as references and then all values in between are compared against them in terms of a ratio [27].

Ingarao et al. [28] have studied the possibility of making the sheet metal forming process more sustainable. The focus has been two main areas:

- Reduction of material wastage
- Reduction in the need for lubrication and cleaning

In order to create the sustainability assessment methodology, the authors [28] proposed to measure and assess the following parameters for sheet metal forming:

- Process energy consumption
- Material wasting
- Emissions
- Steps required in manufacturing cycle
- Lubrication
- Tool life

- Temperature effects

In this study the authors [28] did not consider the social aspect of sustainability. Instead, they focused on the performance, economy and environmental impacts.

Emilio Lebre La Rovere et al. [29] have taken the application of electricity generation and have performed a sustainability study. The authors have chosen some criteria from another paper. They have grouped relevant indicators together in one group. They have proposed a three-point scoring system for each indicator.

- Environmental: Water consumption, specific CO2 emissions, occupied area, non-CO2 emissions, percentage of effective land use.
- Social: Number of direct jobs created, average level of job income, job seasonality.
- Cost: Specific investment, cost–benefit index, percentage of imported inputs.
- Physical performance: Net generation efficiency, average annual availability, construction period and electricity generation potential.

Eastwood et al. [30] have performed an assessment on the manufacturing of bevel gears. The objective was to choose the most sustainable alternative for manufacturing bevel gears. The chosen indicators are listed below:

- Economic impact: Operational cost
- Environmental impact: Input material and non-flyaway content, energy consumption, water consumption, water discharge, GHG and pollutant emissions, landfill waste, recycling waste, hazardous waste
- Social impact: Injuries, lost work days, and chronic illness

To aggregate the score for comparison, the authors used a new approach where all the indictors were calculated, and then one of the alternatives was set as the benchmark. The other alternatives were compared with this process; one indicator at a time using ratios. In the end, the author added all ratios together and deduced which alternative was better.

Yan et al. [31] studied the sustainability performance of machining processes with a case study on face milling. They stated that decisions in machining are mainly considering the cost, material wasted, and material consumed with little or no regard to energy consumption and environmental impact. Thus, the authors aimed to develop a more comprehensive methodology which assesses sustainability performance. The authors put together the following flow chart, shown in Figure 5 to detail the assessment methodology derivation process:

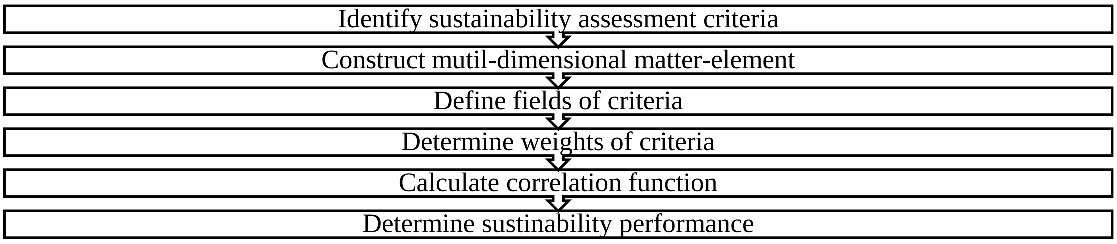


Figure 5: Sustainability assessment derivation methodology [31]

In the first step, the categories selected by the authors were Economic metrics, Environment metrics, and Social metrics. After determining the categories and indicators, the authors showed the completed methodology in Figure 6:

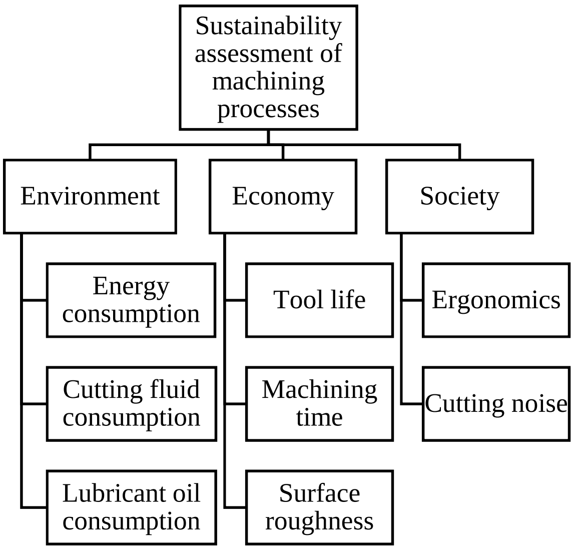


Figure 6: Machining sustainability assessment methodology [31]

The next step would be to create the equations according to which the measured indicators would be analyzed and then scaled for obtaining the category scores. After the individual category scores are obtained, the authors decided to determine weights for each category. These weights would be used for giving different priority for each category, and subsequently may be used for obtaining the aggregate score when assessing a machining process. Rather than assigning arbitrary weights from experience, the authors used the entropy method.

The entropy for each of the categories is calculated based on the indicators contained in that particular category. Equation 1 was used:

$$H_i = -k * \sum_{j=1}^{m} f_{ij} * lnf_{ij}; i = 1,2, \dots, n \text{ [31]} \tag{1}$$

$$where\ k\ is\ constant, k = \frac{1}{lnm}; f_{ij} = \frac{x'_{ij}}{\sum_{j=1}^{m} x'_{ij}}; and\ if\ f_{ij} = 0; then\ f_{ij} * lnf_{ij} = 0$$

The weight of each category is based on the amount of entropy of each category relative to the sum of entropies of all categories. Equation 2 was used:

$$\omega_i = \frac{1-H_i}{n-\sum_{i=1}^{n} H_i}; where\ \sum_{i=1}^{n} \omega_i = 1 \text{ [31]} \tag{2}$$

### 1.3.5. Studies on welding processes.

**1.3.5. Studies on welding processes.** Unlike the aforementioned focus areas, welding has not been receiving much attention from the sustainability perspective. Rather, research on welding has been more focused on developing welding processes and studying their applications on different metals. Moreover, all of these studies drew conclusion based on performance and quality of welding alone. Society, economy, and the environment were rarely considered. Some of these studies are discussed in this section.

Shrivastava et al. [32] have studied the effect of energy consumption and environmental impact on FSW and GMAW. The physical performance indicator measured was the tensile strength, due to its relevance to that particular application. The tensile strength of the FSW joints formed by was found to be 34% stronger than GMAW joints, and 15% stronger than GTAW joints. Moreover, carbon monoxide emissions from FSW were stated to be 3.7 times less than GMAW, and dioxide emissions where 1.6 times less in FSW. The authors stated that little or no non pre and post processing operations are required for FSW when compared to GMAW. Moreover, no filler material is used. They have not considered the equipment cost as a major part in their analysis, and they stated that the operational cost of GMAW is higher than FSW as well; however, the capital cost of FSW is much higher. This implies that in order for

FSW to be the more economical choice, a large production capacity is required. Energy consumption was also considered as an indicator [32].

Suri et al. [33] conducted a similar study, but instead considered FSW and GTAW. Samples welded using FSW at different weld speeds were studied against a GTAW sample. In contrast to the aforementioned paper, not only was the yield strength measured, but plastic behavior, surface appearance, microstructure, strength, hardness, and elongation were also taken into consideration. This indicates that this study was directed towards a performance comparison solely. It is a good contribution for the purpose of the comparison between the two processes, however, for a specific application, where the designed use is well known, all of these indicators may not be required for measurement [33].

K.E.K. Vimal et al. [34] studied SMAW. They aimed to have an improvement which was the reduction of wasted material. The amount of material wastage can be taken from the filler material manufacturer. Emission studies were also performed to measure the impact of the process fumes and dust on the greenhouse effect and the ozone layer. The authors assessed SMAW with various indicators such as energy consumption, wastage, emissions, and employee training. They found that improvements can be done through the optimization of energy consumption. [34]

Blodgett [35] developed an equation to measure the cost of welding. The equation was tailor made for GMAW. Therefore, for the purposes of this thesis, this equation can been generalized to make it applicable for other types of welding processes. It is shown in Equation 3:

$$\mathrm{C(cost)} = \frac{C_l(labour\ cost)}{WM(weld\ mass)} + \frac{C_c(consumable\ cost)}{WM(weld\ mass)} + \frac{C_e(energy\ consumption)}{WM(weld\ mass)} + \frac{C_q(equipment\ cost)}{WM(weld\ mass)}\ [35] \tag{3}$$

S.C. Feng et al. [36] studied the energy consumption and performance efficiency of joining in assembly, with a special case study on welding [36]. The amount of energy can then be calculated to give the amount of energy required for each part produced, and hence, the efficiency in producing that part. In their paper on the categorization of sustainability indicators, the authors [36] also stated the social impact indicators in three different categories:

- Customer
- Community
- Employee

Barbedo et al. [37] did a study to optimize gas metal arc welding (GMAW) and flux core arc welding (FCAW). The authors have realized that these processes are growing in the industry, and that their weld quality is of prime importance and must be optimized. They designed few tests with the aim of finding the best voltage, current, welding speed, etc. to create the best weld. To measure the weld performance, the authors tested the welded samples for:

- Yield strength
- Grain size
- Micro hardness

Mittal et al [38] studied welding dissimilar metals. They studied welding processes for the welding of austenitic steel and ferritic steel pipes. SMAW, GTAW, and a combination of SMAW and GTAW were considered. To quantify the performance of the resulting joints, the authors used the yield strength, ultimate tensile strength, micro hardness, and fracture toughness. GTAW was found to be the best alternative.

As the literature review has discussed, sustainability as a notion has been well established, and it is being applied to applications successively because it provides a more holistic approach for decision making. In addition to that, none of the studies done on welding processes were coming close to a sustainability study. They were more focused on performance. Therefore, it is incredibly important to create and apply a sustainability assessment methodology to welding processes for better decision making, especially in the absence of dedicated assessment tool.

### 1.4. Motivation

The demand for sustainability nowadays is increasing from both the producers and the consumers. This is because pursuing sustainability leads to:

- Increasing profits
- Conserving resources
- Raising society

- Protecting the environment

This thesis aims to produce a sustainability assessment tool for the manufacturing sector, and in particular for welding processes. After a thorough literature review, it has been concluded that there was no research done to perform a complete sustainability assessment for welding processes.

### 1.5. Objective

Having stated the benefits of having a sustainability assessment done before making decisions and with very little sustainability research done in the manufacturing sector, it would be very important to expand the limits of sustainability to include manufacturing. This would render sustainability as the prime decision making target at times of planning. This thesis aims to firstly state the general sustainability assessment notion. This would then be studied and developed for manufacturing processes by recognizing the specifics which distinguish manufacturing as a topic from others when it comes to sustainability. Later, the methodology would be adapted in this thesis specifically for the assessment of welding processes. The following steps detail the approach to be followed to accomplish these objectives:

1. To develop an understanding of the concept of sustainability.
2. To develop a general methodology for out a complete assessment.
3. To adapt the general methodology for the welding assessment.
4. To test this methodology by running a case study.
5. To draw conclusion and suggest future development and.

### 1.6. Thesis Layout

The layout of this thesis will be as follows. The methodology of this thesis will be discussed first. Next, the general sustainability will be stated. This would include the main concept, and categories for assessment found in the literature. The next section would discuss the methodology adapted for welding applications. This will be done by carefully specifying indicators for the chosen categories with a detailed explanation of the choices. The case study would follow, and would be applied to the suggested methodology on three particular welding processes to find the most sustainable one. Finally, the thesis will be concluded by summarizing the findings, and stating some future development measures.

# Chapter 2. Sustainability Assessment Methodology

## 2.1. General Frame-Work for Sustainability Assessment

In order to develop a sustainability assessment methodology, a process flow was established. This section outlines general frame-work for the sustainability assessment methodology.

The first step is defining the sustainability performance categories. They would form the main basis of the methodology by generalizing what would be measured and assessed. Categorization would give the user a great deal of flexibility. It allows the user to assess sustainability performance in different areas separately. Moreover, having defined the categories but not the indicators would allow for more flexibility to the user in changing the relevant indicators for a particular study. Ultimately, the results of these categories might also be combined to give an overall score for the product/process, if required.

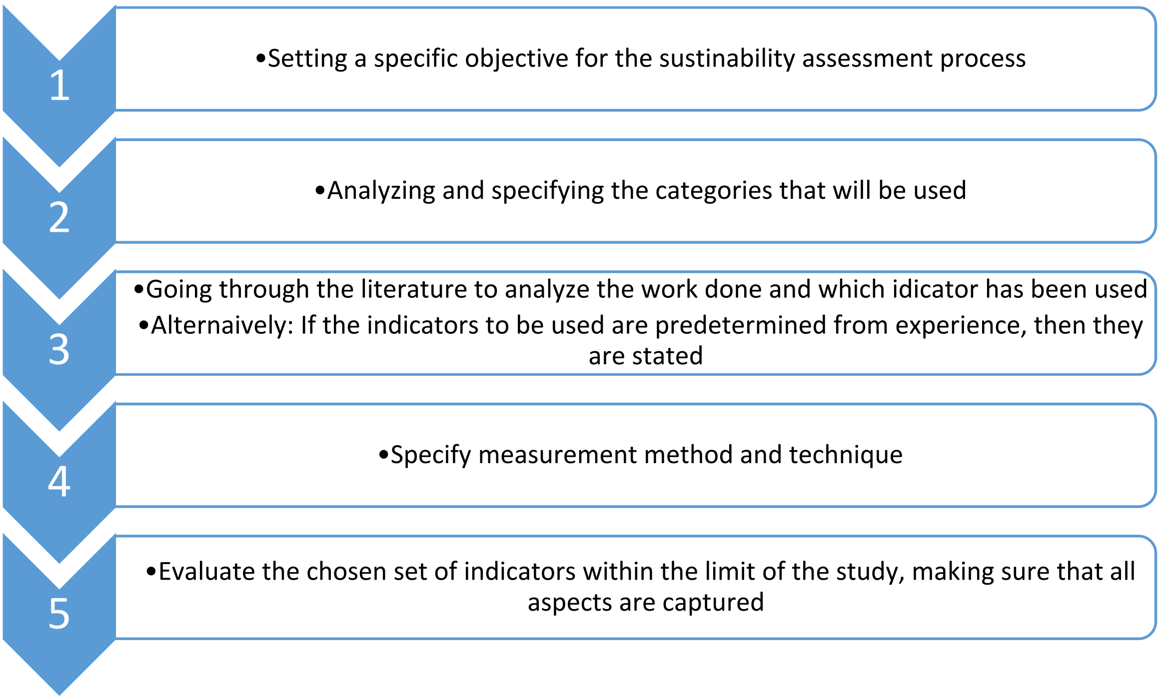
The National Institute of Standardization and Technology's (NIST) categorization to group indicators into five main categories [13]:

1. Environmental stewardship
2. Economic growth
3. Social well-being
4. Performance measurement
5. Technological advancement indicators

These categories need to be assigned relevant indicators so that a holistic approach can be used. By adapting the steps highlighted in the literature, the process flow for selection of the indicators was generated. This would be followed by selecting the indicators for each category. The flow chart in Figure 7 illustrates this process. After the selection of the indicators from existing sets, the evaluation may be done before finalizing their usage. According to C.B. Joung et al. [13] the indicator sets can be evaluated by:

1. Measurability
2. Relevance
3. Understandability
4. Reliability

5. Data accessibility
6. Periodic collection of data
7. Long term availability



- Setting a specific objective for the sustinability assessment process
- Analyzing and specifying the categories that will be used
- Going through the literature to analyze the work done and which idicator has been used
- Alternaively: If the indicators to be used are predetermined from experience, then they are stated
- Specify measurement method and technique
- Evaluate the chosen set of indicators within the limit of the study, making sure that all aspects are captured

Figure 7: Sustinability assessment methodology flowchart

## 2.2. Welding Sustainability Assessment Categories and Indicators

As has been stated in the objective section, this study aims to produce a sustainability assessment methodology for welding processes. The details of this methodology is discussed in this section.

Technological advancement as a category would not be taken into consideration in this methodology because it is designed for the study of existing process without applying any improvements. Therefore, a study of existing processes should not contain this category.

Moreover, the performance category would be taken as a separate category as highlighted by NIST. Many researchers have studied various alternatives towards achieving the same goal. In that case the performance criterion is first decided and achieved through the alternatives, then the resources used are evaluated from an economic, environmental, and social point of view. The performance would be similar and hence would need a separate category. In spite of that, the aim of this work is to study processes which have completely different characteristics, including their performance.

The four main assessment categories, and their relevant indicators have been chosen in accordance with literature. These are discussed below:

**2.2.1. Physical performance.** This category would score the welding process with regards to the physical properties of the weld. As stated in the literature, there are various indicators that can be used for the measurement of this category. These indicators are used to measure and quantify material properties including:

- Yield strength
- Young's modulus
- Shear modulus
- Roughness
- Toughness
- Hardness

These would help determining the resulting mechanical properties of the welded area with respect to the base metal. The aim is to have mechanical properties as close as possible to the respective base material ones. Due to the great number of possible properties to select as indicators, for this study only two were considered. Choosing these indicators from list of mechanical properties will be justified below:

- Yield strength

This material property was chosen as it is a very important indicator and considered as a main failure criterion. It is used to determine the amount of load that the work piece can take before yielding, and generally yielding is considered as the point of mechanical failure. For a welded work piece, this value is usually less than the base material value because of material property changes with the generation of heat during the process. Nevertheless, it is very important to ascertain that the weld does not significantly reduce the overall strength of the work piece and becomes a weak point.

This indicator has been commonly used by nearly all researchers who have done any study on welding process. These studies have been mentioned in the literature review including Shrivastava et al. [32], Barbedo et al. [37], and Suri et al. [33].

- Impact toughness

This material property is a very important indicator when it comes to welded work pieces. Usually any welded area is not as tough as the base material. So, the relative decrease in the toughness must be measured to determine if the work piece can satisfy toughness requirements.

**2.2.2. Environmental impact.** One of the greatest growing concerns regarding all manufacturing processes is the impact on the environment. This happens in a number of ways varying by the particular application. Some of the environmental concerns are:

- Gas emissions
- Waste production
- Consuming non-renewable resources

For this application of the methodology on welding processes, the indicators which were considered are the emissions, wastage, and auxiliary material usage.

- Emissions and carbon footprint

Emissions are very common to all manufacturing processes. Therefore, a study such as this, which includes an environmental impact aspect, must quantify the emissions associated. These emissions could include any emission from the welding process in addition to the carbon footprint produced through the electricity consumed. The emissions are compared to the OSHA limit from the weld filler material safety data sheet if applicable.

- Material wastage

Due to many reasons, manufacturing processes tend not to completely utilize the raw material, thus a certain amount of this material is wasted beyond further use. In welding process, this amount is usually small, but it must be captured for the sake of the study.

- Auxiliary material

As mentioned in the literature review section, some welding processes use auxiliary material for shielding the hot, reactive weld from the atmosphere. This shielding is mostly removed after the weld cools down either by hammering to break solidified slag, or it may diffuse in to the atmosphere if the shielding is in the form of a gas. Nevertheless, when auxiliary material is not recovered, the usage must also be captured and quantified.

**2.2.3. Economic impact.** The economic impact category should be taken into consideration as it measures how much would a user need to pay to get the corresponding physical performance, environmental impact, and social impact. Moreover, this category has to be measured and analyzed very accurately. All inputs need to be considered to produce a useful result.

The economic impact is calculated using an equation which was developed by Blodgett [35]. The equation was tailor made for GMAW. Therefore, for the purposes of this study, this equation has been modified and generalized to make it applicable for other types of welding processes. It will be stated later on in this section. It includes:

- Consumable cost
- Equipment cost
- Operating cost
- Energy consumption

**2.2.4. Social impact.** In their paper, in the categorization of sustainability indicators, Shaw Feng et al [36] have discussed the social impact indicators in three different categories:

- Customer
- Community
- Employee

The main focus of the social impact indicator in this study are aimed at the employee (welder). In this category, the authors imply that there are three indicators that can be considered:

- Health and safety
- Development
- Satisfaction

This study would mainly focus on the first indicator, health and safety, as it seems to be the most relevant to the study on welding. Therefore, the only indicator that would be considered for the social impact would be the health and safety of the welders.

This will be measured by the risk of injury and the cost of injury. These data are taken from record, experience and statistical data for each welding process, and then compared with the average incident rate per year.

## 2.3. Category Equations

**2.3.1. Normalization and scaling.** The various indicators discussed in the previous section should be measured and recorded in a sustainability assessment study. These indicators may be compared among different processes to evaluate the performance of each of the processes in that particular indicator. This would be greatly beneficial for pinpointing the particulars of a process. However, this would be tedious and confusing when a great number of indicators is used. This is why the performance of indicators in a particular category must be added in a particular manner to reduce the comparison from various indicators, to a four category scores only.

It must be stated that adding the performance of all individual indicators together would prove more difficult than a simple sum or arithmetic mean. This is because the different indicators have been measured in different dimensions even when measured within the same category, which is why the indicators in each category should be first normalized and scaled Then scaling method should depend on the indicator and category [17].

After the indicators have been normalized and scaled, they can be aggregated to output the score for each category. Rajesh et al. [39] suggested that depending on the type of scaling, the method with which the indicators can be aggregated varies. When creating ratios, the comparability of the indicator ratios should help determine the aggregation technique as shown in Table 6:

Table 6: Arithmetic mean and geometric mean [39]

| | Non-comparability | Full comparability |
|---|---|---|
| Interval scale | Dictatorial ordering | Arithmetic mean |
| Ratio scale | Geometric mean | Any homothetic function |

The indicator ratios would be judged as they are created. Depending on whether or not the indicator ratios within each category are comparable with each other, the decision to go with an arithmetic or geometric mean would be made. However, due to the specifics of this methodology, the arithmetic mean was used for all the categories.

Most of the chosen indicators were measured in different dimensions. However, each indicator was then analyzed and transformed into a non-dimensional number in one way or another. This would ease the comparison between categories for different processes. To elaborate further, the numerical measurement technique (equation) and its respective dimensions for all four categories are shown below:

- Physical performance:

In order to develop the equation to quantify the physical performance score, both indicators have to be combined in an arithmetic mean. However, as they both are measured in different dimensions, they first have to be scaled similarly to be applied to an arithmetic mean properly. In this case, both the weld yield strength and the weld impact toughness will be divided by that of the base metal. This guarantees that both indicator ratios vary from 0 to 1. The arithmetic mean can then be formed as shown in Equation 4:

$$Physical\ Performance = \frac{\frac{yield\ strength_{weld}}{yield\ strength_{base}} + \frac{toughness_{weld}}{toughness_{base}}}{2} \tag{4}$$

- Environmental impact:

In order to sum up the various effects from the welding processes on the environment, the indicators need to be scaled equally and then averaged. For the weld emissions, the wasted material emitted to the atmosphere is first calculated. The composition of this emitted material should then be determined from the respective filler MSDS. These emitted compositions should then be compared to the allowable limits from an official safety organization such as OSHA. This ratio would be non-dimensional, and Equation 5 would be used for this calculation is:

$$Weld\ Emissions = \frac{wastage * \sum_{n=1}^{number\ of\ components\ in\ filler} \frac{\%component}{limit}}{number\ of\ components\ in\ filler} \tag{5}$$

To normalize the CO2 footprint, the amount of CO2 produced must be compared to the CO2 limit. The CO2 footprint may be calculated using the local electricity authority rate. In the UAE the rate is sown in Equation 6:

$$CO_2\ footprint = \frac{power\ consumption(kwh)}{2} \tag{6}$$

The limit may be calculated by first obtaining the CO2 footprint limit for the electricity authority. This amount can then be scaled to match the welding time as shown in Equation 7:

$$CO_2\ limit = (montly\ limit) * welding\ time(month) \tag{7}$$

The last environmental indicator is any weld mass wasted. This would include any mass which will be disposed of (cut-off) or which has disappeared (emitted) after the welding process. This value would be compared to the weld mass. This concludes the normalization and scaling of the environmental indicators, and the complete environmental impact is shown in Equation 8:

$$Environmental\ Impact = 1 - \frac{emissions_{weld} + \left(\frac{CO_{2,foot\ print}}{CO_{2,limit}}\right) + \left(\frac{Aux\ material}{Aux\ material_{limit}}\right) + \left(\frac{wastage}{mass_{weld}}\right)}{4} \tag{8}$$

- Economic impact:

The equation which is used to quantify the cost of the weld was developed by Blodgett [35]. However, the result of that equation is a currency. To render the outcome dimensionless, this total cost should be compared to the cost of the two individual welded sections. Not only would this give a normalized and scaled outcome, but the result of the modified equation would give a hint of the amount of extra money needed to form the joint relative to the cost of the raw material. The resulting equation is Equation 9:

$$Economical\ impact = 1 - \frac{time_{weld} * cost_{labor} + cost_{consumable} + cost_{equipment} + energy * cost_{energy}}{cost_{part}} \tag{9}$$

- Social impact

Fortunately, the social impact indicator, incident rate, is in itself normalized and scaled. Therefore, an arithmetic mean could be directly applied to the selected incident rates from the literature. This mean would compare the incident rate of that particular welding process, to the highest occurring incident rate among manufacturing and construction processes for that particular year.

$$Social\ impact = Average\left(\frac{incident\ rate_{2013}}{maximum\ incident\ rate_{2013}}, \frac{incident\ rate_{2014}}{maximum\ incident\ rate_{2014}}, \ldots\right) \tag{10}$$

**2.3.2. Category weights.** The equation results or category scores produced from the equations are used as a measurement to the performance of each process in that particular category. When a comparison between different processes is made, these scores can tell where a particular process leads the others, or where it may lack. This would enable any development plan to identify a specific category as a target for development in the future. Furthermore, once a category is identified, a comparison between the indicators within that particular category might be implemented to see exactly what the particular process excels or lacks at. In case a particular indicator is hindering the performance of the process, studies may be directed at improving the performance of that particular indicator.

However, in a decision-making environment, it may be irrelevant to help developing a process. Studies are made to decide the best existing process and implement it in a particular application immediately. Thus, it would be more important to combine the results of all categories into a single score. It would be intuitive to claim that taking the mean would be a simple and effective solution. However, with the existence of four different categories, various individuals who may use this methodology would state that some the categories may be more important than others in a particular application. Therefore, a weighted average may prove to be more appropriate to output the aggregate score.

Tomas et al. [18] suggested two ways in which the weights may be determined. The first of which is to have a panel of experts to meet and discuss the methodology. The meeting would conclude with determining the weights based on the experts' experience. The second method involves creating a survey and distributing it to various individuals who deal with the issue and ask for a wider variety of opinions in order to eliminate any bias. The study adopted the latter method and a survey was created and distributed to various individuals from the industry, and the academic fields. This would allow this methodology to be as unbiased and as objective as possible.

Although this would leave the indicators of equal weight within each category in the calculation, the methodology in this thesis assumed that all indicators in a category can be taken of equal weight, and that the category weight would take care of giving the importance where necessary. Nevertheless, if deemed necessary for other applications, the methods stated by Tomas et al [18] may be carried forward to the indicators to provide experts with more relevant results to a particular application or study.

**2.2.3. Aggregation.** For the aggregation of the weighted categories, Rajesh et al. [39] have suggested six methods to aggregate the scores into a single score besides the arithmetic mean. These are stated in the Table 7:

Table 7: Aggregation methods [39]

| Method | Equation |
|---|---|
| Sum | $= \sum_{i=1}^{N} Category$ |
| Indicators above mean minus indicator below mean | $= \sum_{i=1}^{N} \left[\frac{x}{x_{mean}} - (1+p)\right]$<br>$where\ p\ is\ an\ arbitray\ threshold\ above\ and\ belowthe\ mean$ |
| Ratio from the mean | $= \frac{\sum_{i=1}^{N} \frac{w*y}{x_{mean}}}{\sum_{i=1}^{N} w}; where\ y = \frac{x}{x_{mean}}\ and\ w\ is\ the\ weight$ |
| Annual differences over consecutive years | $= \frac{\sum_{i=1}^{N} \frac{w*y}{x_{mean}}}{\sum_{i=1}^{N} w}; where\ y = \frac{x - x_{old}}{x_{mean}}\ and\ w\ is\ the\ weight$ |
| Standardized values | $= \frac{\sum_{i=1}^{N} \frac{w*y}{x_{mean}}}{\sum_{i=1}^{N} w}; where\ y = \frac{x - x_{mean}}{\sigma_{mean}}\ and\ w\ is\ the\ weight$ |
| Re-scaled values | $= \frac{\sum_{i=1}^{N} \frac{w*y}{x_{mean}}}{\sum_{i=1}^{N} w}; where\ y = \frac{x - x_{min}}{x\_range}\ and\ w\ is\ the\ weight$ |

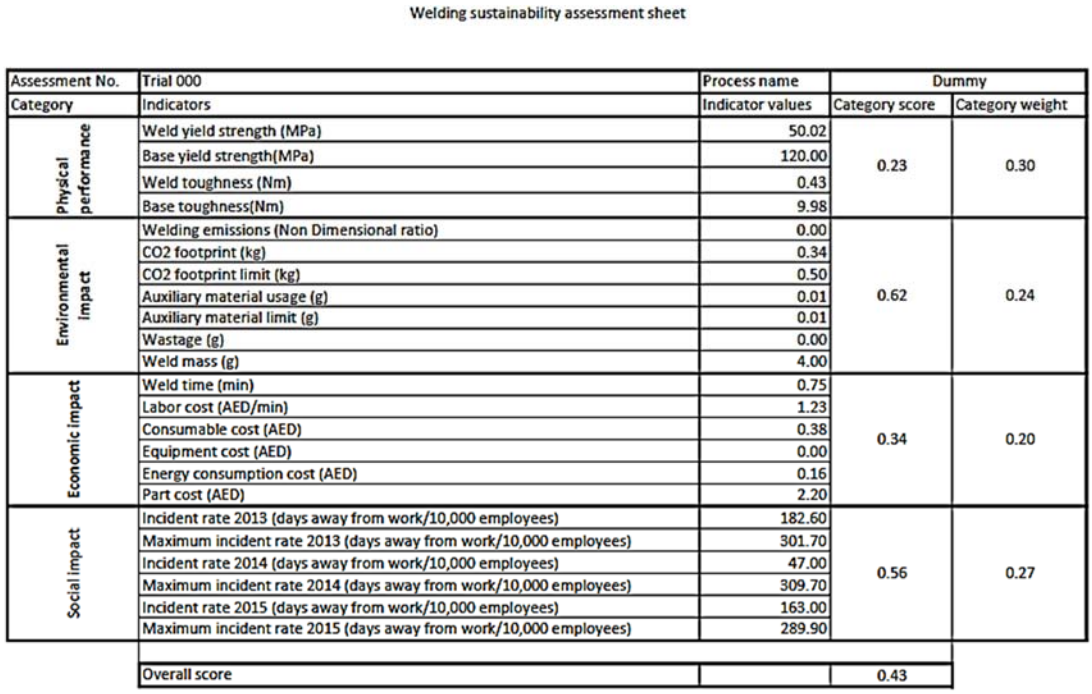
The first method was chosen to be used in this thesis. The equation is applied by obtaining the relative weights of each of the categories and then performing a sum.

Once these weights have been collected, a simple equation would be used to find the overall weighted average of the performance of each process, shown in Equation 11:

$$Aggregate\ score = Physical\ Performance * weight + Environmental\ Impact * weight + Economical\ Impact * weight + Social\ Impact * weight \quad (11)$$

## 2.4. Representation

In order to input that aforementioned values in to the equations, a simple calculation sheet was created to simplify and systemize the process of obtaining the scores. This calculation sheet is shown in Figure 8:



Welding sustainability assessment sheet

| Assessment No. | Trial 000 | Process name | Dummy | |
|---|---|---|---|---|
| Category | Indicators | Indicator values | Category score | Category weight |
| Physical performance | Weld yield strength (MPa) | 50.02 | 0.23 | 0.30 |
| | Base yield strength(MPa) | 120.00 | | |
| | Weld toughness (Nm) | 0.43 | | |
| | Base toughness(Nm) | 9.98 | | |
| Environmental Impact | Welding emissions (Non Dimensional ratio) | 0.00 | 0.62 | 0.24 |
| | CO2 footprint (kg) | 0.34 | | |
| | CO2 footprint limit (kg) | 0.50 | | |
| | Auxiliary material usage (g) | 0.01 | | |
| | Auxiliary material limit (g) | 0.01 | | |
| | Wastage (g) | 0.00 | | |
| | Weld mass (g) | 4.00 | | |
| Economic impact | Weld time (min) | 0.75 | 0.34 | 0.20 |
| | Labor cost (AED/min) | 1.23 | | |
| | Consumable cost (AED) | 0.38 | | |
| | Equipment cost (AED) | 0.00 | | |
| | Energy consumption cost (AED) | 0.16 | | |
| | Part cost (AED) | 2.20 | | |
| Social impact | Incident rate 2013 (days away from work/10,000 employees) | 182.60 | 0.56 | 0.27 |
| | Maximum incident rate 2013 (days away from work/10,000 employees) | 301.70 | | |
| | Incident rate 2014 (days away from work/10,000 employees) | 47.00 | | |
| | Maximum incident rate 2014 (days away from work/10,000 employees) | 309.70 | | |
| | Incident rate 2015 (days away from work/10,000 employees) | 163.00 | | |
| | Maximum incident rate 2015 (days away from work/10,000 employees) | 289.90 | | |
| | Overall score | | 0.43 | |

Figure 8: Sustainability assessment sheet

In order to represent the outcome of the sustainability assessment, rather than viewing numbers, it is suggested that illustrating the result would give a more eye friendly result. This can easily be done on using a variety of colorful graphical representations. However, the aim of having a graphical representation for the sustainability assessment is to give the hypothetical decision makers as much information as possible from simply examining one figure. This section aims to select a method for representing the assessment information with the following characteristics:

- Display aggregate score
- Display individual category score
- Display category weighs
- Easy and quick to read
- Does not appear technical

From literature, it was found that quite a few representation methods are used. The most common one was a radar plot. It has the ability to display the aggregate score, the category scores, and is fairly easy to read, but it usually looks technical. Other authors chose to go with a more traditional bar chart representation. This is very easy to read, and would be able to display the values required. Although this method is easy to interpret, its usability is hampered by the fact that it does not directly provide the aggregate scores for each of the alternatives. Rather, the scores from each category have to be extracted, and then the aggregates need to be shown separately.

As none of the discussed representation methods was found to be perfect, this thesis proposed a new representation method using the advantages of the aforementioned techniques, and trying to avoid the disadvantages. An area graph is suggested for representation of sustainability assessment. The bar width would represent the category weights. The bar height would represent the category score, and the overall score is also shown on the figure. This is illustrated in Figure 9.

This representation holds many advantages such as that the weightage, category score, and aggregate score can all be seen immediately from a single figure. In addition to that, the area can be perceived and understood by users more easily that lines as bar provide two dimensional representations. The ultimate aim of producing a colorful, and informative representation is to provide hypothetical end users with a sort of ‘stamp’ that could be branded on processes or products to show sustainability information that can be understood by all people.

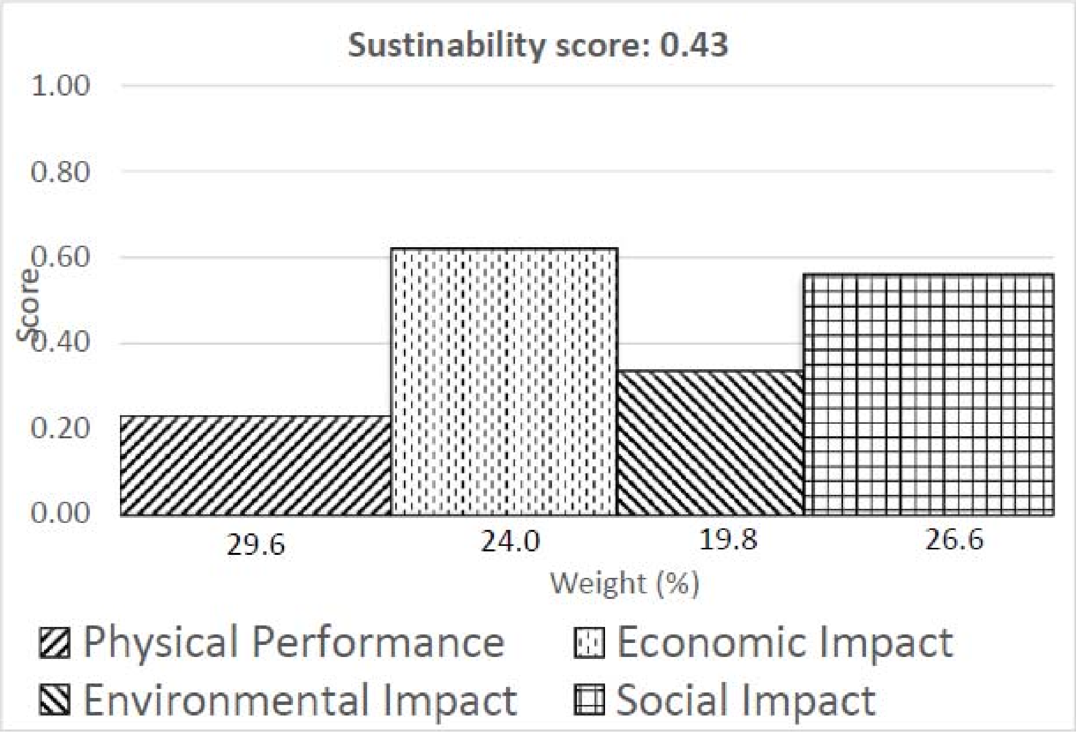


Figure 9: Proposed sustainability result representation

## 2.5. Summary

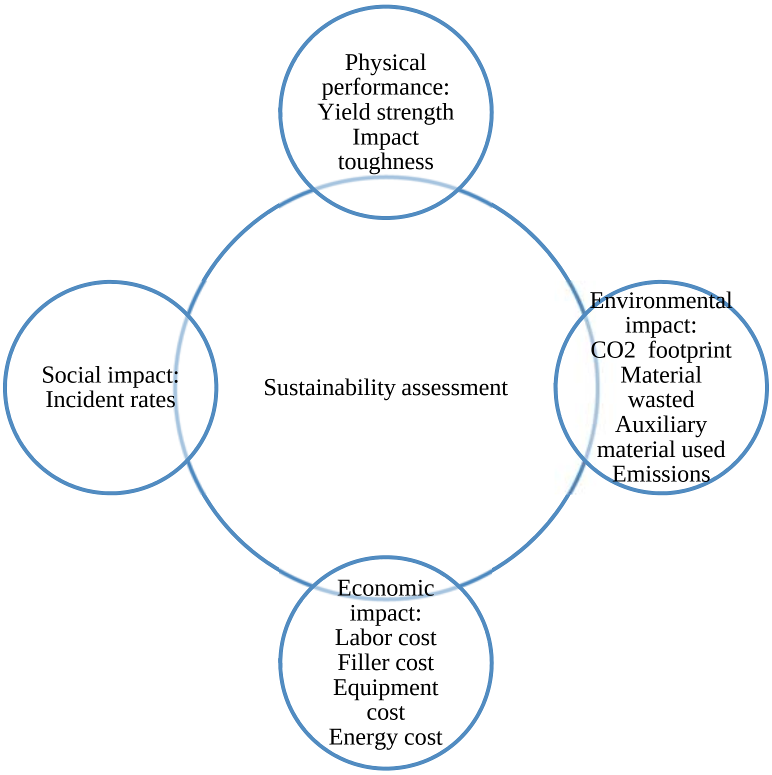


Figure 10: Sustainability assessment summary

This section has discussed in detail the development of the sustainability assessment methodology. First, a general methodology was extracted from the literature. This identified the general requirements of creating an assessment methodology, namely categories to be considered. Then the general methodology was adapted to suit the requirement of welding processes in particular. This was done through developing an understanding about which categories will be carried on from the general methodology, and how the indicators will be selected to represent each of them. These categories and indicators are further summarized in Figure 10.

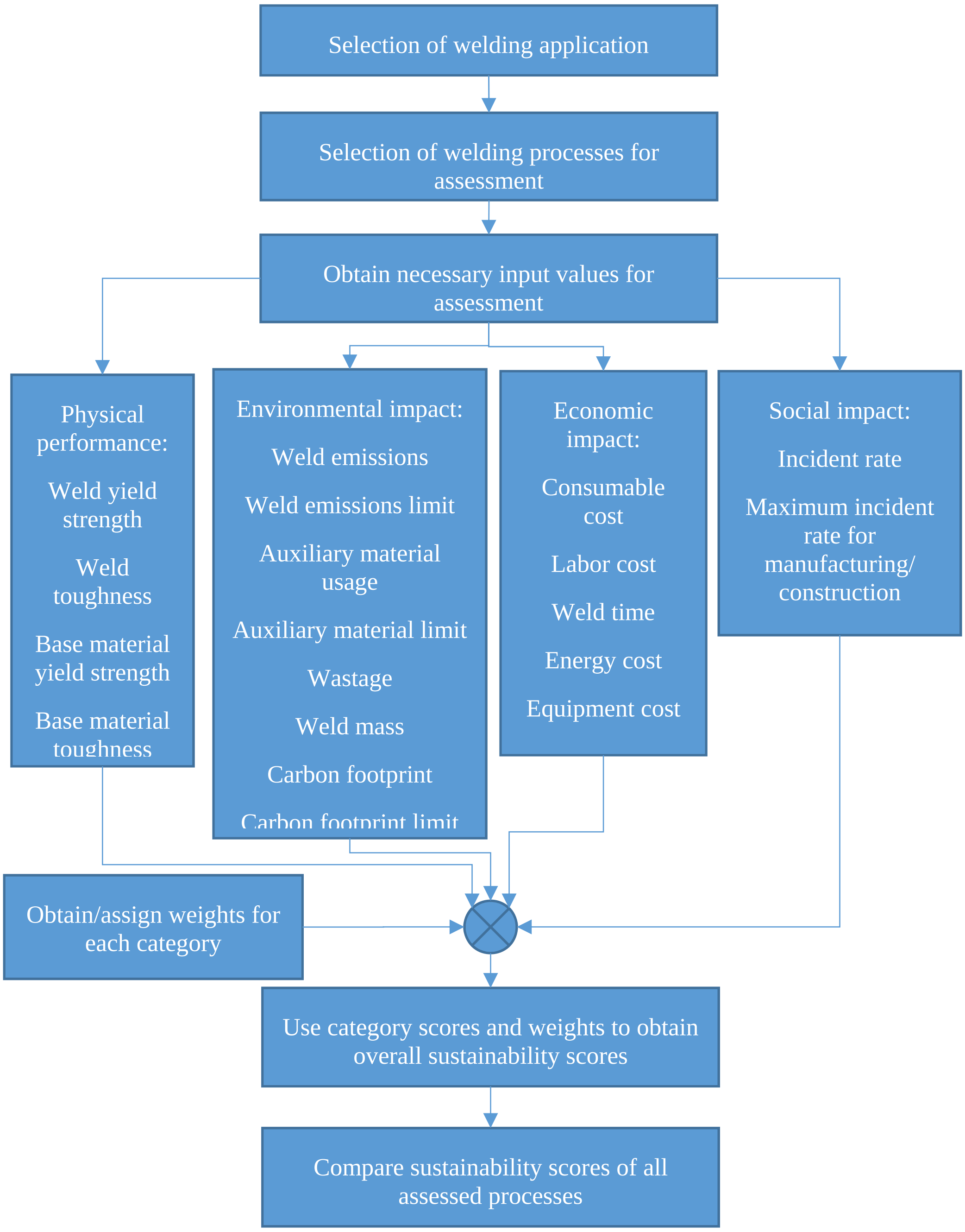


Figure 11: Sustainability assessment flowchart

This was followed by the selection of the indicators, and the forming of the equations that will be used to obtain the relevant scores. The results of these equations would quantify the category score. These category scores would be combined through a weighted average technique to obtain the overall sustainability score. Figure 11 details the process from the start of the assessment all the way to obtaining the overall sustainability score.

# Chapter 3. Case Study

## 3.1. Introduction

This section discusses the case study used to demonstrate the capability of the suggested sustainability assessment methodology. Three welding processes have been chosen as candidates for this study and were assessed from a sustainability point of view. These processes were studied for the welding of Aluminum alloy 5083. These processes are:

- Gas Tungsten Arc Welding (GTAW)
- Gas Metal Arc Welding (GMAW)
- Friction Stir Welding (FSW)

Parameters identified in the methodology were measured before, during and/or after the welding as appropriate. Detailed descriptions of all the measurements which were taken are listed below:

Physical performance:

- Yield strength: measured after the welding process. Specimens were cut from the welded plates and tested using the tensile testing machine.
- Impact toughness: measured after the welding process. Specimens were cut from the welded plates and tested using the Charpy Impact Toughness machine.
- Initial temperature of the plates: to ensure that the plate is not too hot for the experiment, and to keep a record of the conditions in case replication of the specimen is required later on.
- Welding temperature: to keep a record of the conditions in case replication of the specimen is required later on.
- Weld length.
- Plate thickness.

Environmental impact:

- Auxiliary material flow rate: to get the mass of auxiliary material used for welding.
- Filler diameter: to get the mass of filler used.
- Final welded mass: this is the weight of the welded plates.

Economic impact:

- Plate weight: weight of the plates before welding.
- End preparation time: time used for the bevel preparation for the arc welded samples, and the starting hole drilling for FSW.
- End preparation energy: energy used for the bevel preparation for the arc welded samples and the starting hole drilling for FSW, which was added to the total energy consumed by the process.
- Welding time.
- Welding energy consumption.
- Grinding time: measured for the FSW as some grinding was required to remove burs after welding.
- Grinding energy: measured for the FSW as some grinding was required to remove burs after welding, and would add to the total energy used for the process.

Further information was acquired to complete this study which could not be measured, and are listed below:

- MSDS of filler material
- Cost of filler material
- Cost of FSW tool
- Safety and health statistics
- Cost of electricity
- Carbon footprint rate

## 3.2. Welding Processes Details

**3.2.1. Gas tungsten arc welding (GTAW).** GTAW is an arc welding process that uses a non-consumable tungsten electrode to create an arc through a potential difference between the electrode and the work piece. Inert gas is also fed through the same electrode for shielding. This arc generates energy that will be used to melt and fuse a consumable filler rod. This rod is fed manually and therefore this type of welding requires a good level of craftsmanship. The process schematic is shown in Figure 12.

**3.2.2. Gas metal arc welding (GMAW).** GMAW is an arc welding process which uses an inert gas (Argon) for the shielding of the filler weld from oxidization.

The filler is originally in the form of a wire wound on a spool. The wire filler and the gas are both simultaneously fed from the same nozzle on to the welding area.

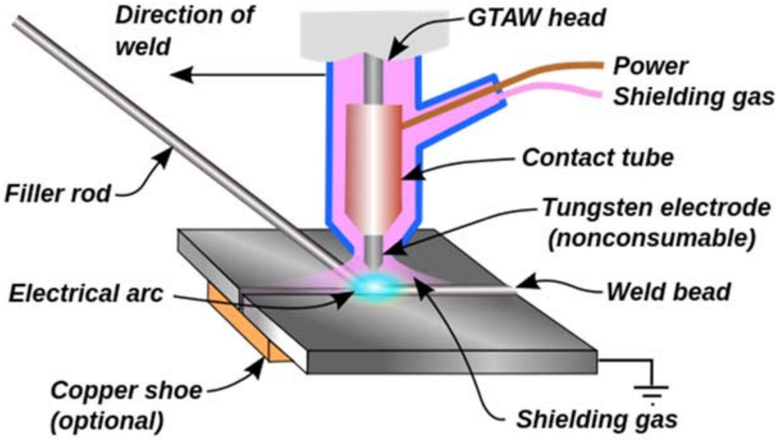


Figure 12: GTAW process [40]

A high potential difference between the filler material and the work piece produces an electrical arc as the wire approaches the work piece. This arc produces a large amount of heat which melts the filler and fuses it with the work piece. The process schematic is shown in Figure 13:

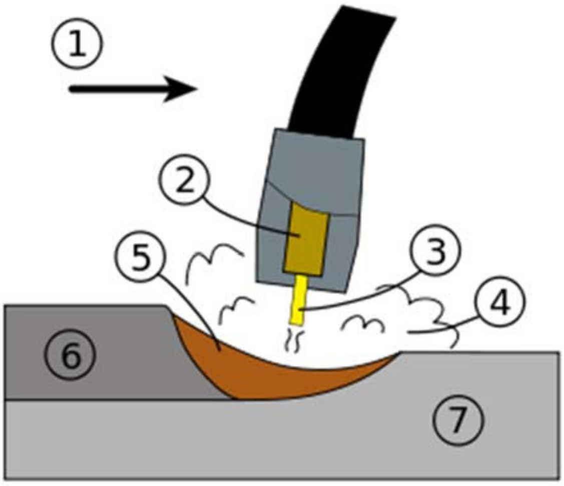


Figure 13: GMAW process [41]

**3.2.3. Friction stir welding (FSW).** FSW is a solid state joining process which was initially developed for the joining of aluminum and other similar soft metals [42]. This process requires a non-consumable tool that rotates and translates along the joint of two parts. Heat is created by the friction between the rotation of the tool and the surface of the joint. The tool then traverses the length of the joint to complete the weld [43].

FSW does not require cover gas or flux. In FSW the main two parameters that are controlling the process are the tool rotational and translational speeds [44]. The rotational speed affects the temperature of the tool and surface, while the translational speed is the one responsible for the movement of the tool in the desired direction [45]. The process is very sensitive to the processing parameters, and these parameters have to be chosen carefully to successfully weld a specific material with a specific thickness [10]. The process schematic is shown in Figure 14:

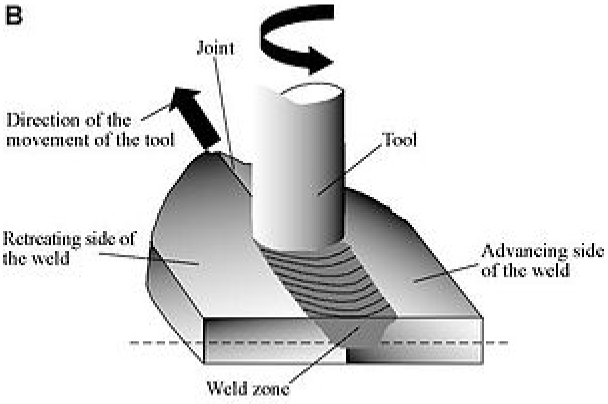


Figure 14: FSW process [46]

## 3.3. Experimental Works

**3.3.1. Design of experiment.** These processes were used for the assessment of welding Aluminum Alloy 5083. The stock used was 5 mm thick plate. Two similar plates of this alloy were welded using the aforementioned processes. These plates were fastened to a jig which served as a mounting to fix the two halves in place, and as weld backing as required by the welding specification procedure [47].

Figure 15: Plates fixed on weld backing jig

The plates followed a certain nomenclature that would allow full identification. This means that from the name of the sample, the process and trial would be identified. The nomenclature is as shown in Table 8:

Table 8: Sample nomenclature

| Process | First character | Second character | Third character |
|---|---|---|---|
| GTAW | S | T | Trial number (1, 2, 3, etc.) |
| GMAW | S | M | Trial number (1, 2, 3, etc.) |
| FSW | S | F | Trial number (1, 2, 3, etc.) |

By applying the nomenclature, the plate in the photograph was identified as a GMAW sample of second trial. In total, three GTAW, three GMAW, and nine FSW samples were made. Only the samples which provided a good visual inspection result were carried forward for testing. In case the visual result was not satisfactory, another sample was created. For GMAW and GTAW, the first sample was enough to optimize the process parameters. FSW, on the other hand, was not easy to optimize and many samples failed visual inspection. This is why the number of the samples is relatively higher for FSW

The GTAW, GMAW and FSW equipment were set up and run by an experienced welder in a well-equipped lab. The equipment is shown in Figure 16 and 17:

Figure 16: GTAW tool (left) [48] and GMAW tool (right) [49]

Figure 17: FSW welding tool in CNC milling machine [50]

#### 3.3.1.1. *GTAW.*

- Sample preparation
  - Edges were smoothened with filing (grinding to be avoided due to heat generation)
  - Degrease using solvents, and dry using a clean cloth (if necessary)
- Weld backing

Temporary weld backing of ½” wide, 1 mm deep would be required as shown Figure 18:

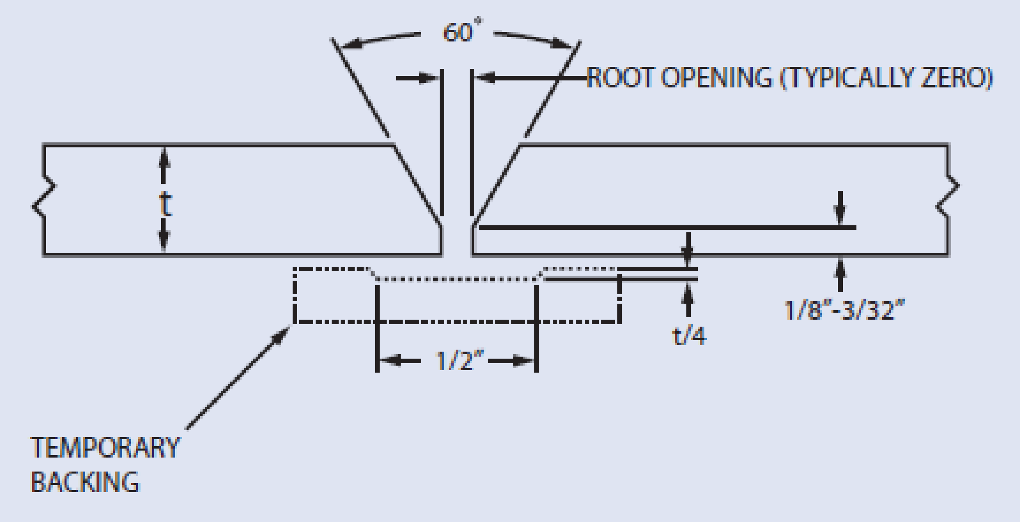


Figure 18: Weld backing [47]

- Process parameters

Table 9: GTAW process parameters [51]

| Joint space (in) | Weld passes | Electrode diameter (in) | DC (amps) | Voltage (V) | Argon gas flow (l/m) |
|---|---|---|---|---|---|
| 0 | 1 | 3/32 | 200 | 260 | 8 |

### 3.3.1.2. *GMAW.*

- Sample preparation
    - Edges were smoothened with filing (grinding to be avoided due to heat generation)
    - Degrease using solvents, and dry using a clean cloth (if necessary)
- Weld backing

Temporary weld backing of ½" wide, 1 mm deep would be required as shown in Figure 19:

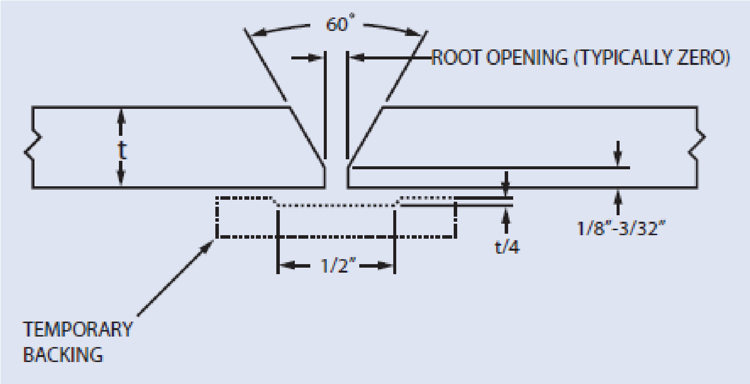


Figure 19: Weld backing [47]

- Process parameters

Table 10: Process parameters [51]

| Joint space (in) | Weld passes | Electrode diameter (in) | DC (amps) | Voltage (V) | Argon gas flow (l/m) |
|---|---|---|---|---|---|
| 0 | 1 | 1/32 | 104 | 23 | 8 |

### 3.3.1.3. *FSW.*

- Sample preparation
    - Edges were smoothened with filing (grinding to be avoided due to heat generation)
    - Degrease using solvents, and dry using a clean cloth (if necessary)

- Process parameters
    - RPM=900rpm
    - Feed rate=100mm/min

**3.3.2. Specimen design.** After the welding was completed and welded plate samples were chosen for testing, the plates were cut using the CNC milling machine according to the specimen size.

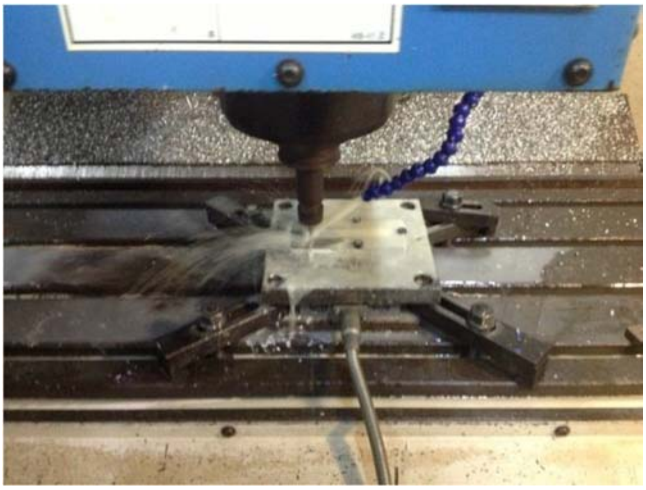


Figure 20: Specimen cutting in the CNC milling machine [50]

**3.3.2.1. *Tensile test specimen.*** Figure 21 and Table 11 shows the dimensions of the tensile test samples which were cut from the welded plates:

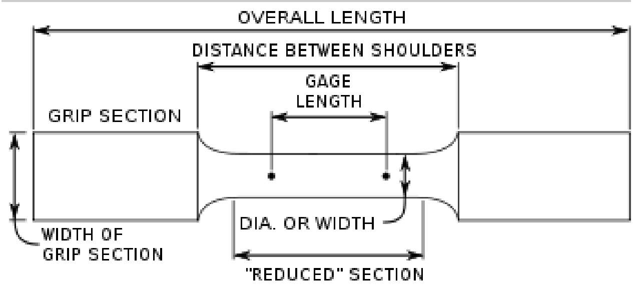


Figure 21: Tensile test specimen [50]

Table 11: Tensile specimen design [50]

| Width (mm) | Fillet radius (mm) | Overall length (mm) | Reduced section length (mm) | Grip section length (mm) | Width of grip section (mm) |
|---|---|---|---|---|---|
| 10 | 4 | 57 | 20 | 12.5 | 20 |

The length of the welded area allowed for 5 samples to be cut from a single welded plate. This was seen to be a sufficient number of samples to get a good average result. These samples were tested using the tensile testing machine. The tensile testing machine and the samples cut from the main welded plate are shown in Figures 22 and 23:

Figure 22: Tensile testing machine

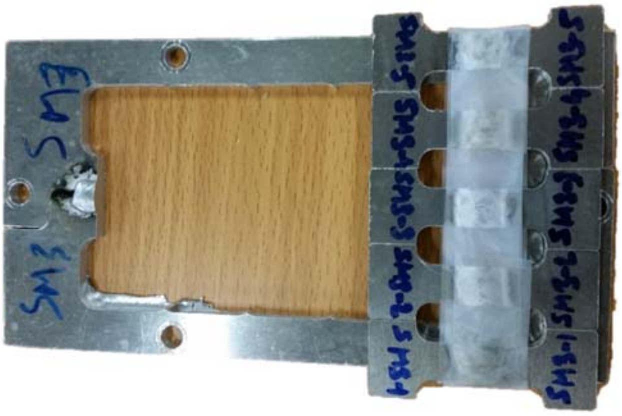


Figure 23: Welded plate with tensile specimens cut

Each of the specimens cut from this plate was given a suffix to help trace the sample from which the specimen was cut. The nomenclature would also identify the location of the specimen along the weld length. Figure 24 and Table 12 explain the nomenclature:

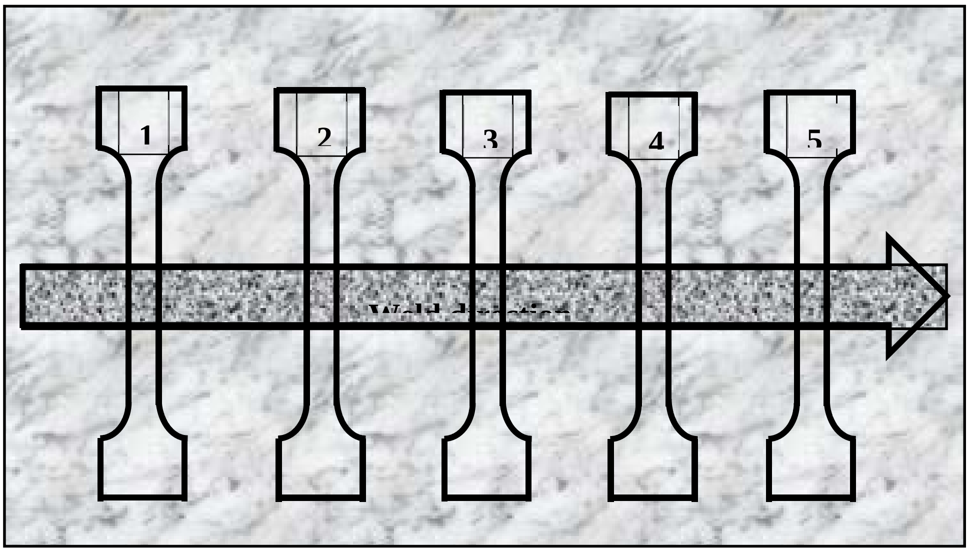


Figure 24: Tensile specimen approximate locations

Table 12: Tensile test specimen nomenclature

| Process | Sample name | Suffix |
|---|---|---|
| GTAW | STX- | Location of specimen (1, 2, 3, etc.) |
| GMAW | SMX- | Location of specimen (1, 2, 3, etc.) |
| FSW | SFX- | Location of specimen (1, 2, 3, etc.) |

To elaborate, a specimen with the name SM2-4 belonged to the second trial of GMAW at the fourth location of the tensile test specimens. Identifying the location might help justify some results later on in the discussion stage.

Figure 25: Tensile test specimen after testing

The testing was repeated for all samples, and all the data was recorded for further sustainability analysis. A tensile test specimen is shown in Figure 25 after the tests have been completed.

**3.3.2.2. *Impact test sample.*** Figure 26 below shows the dimensions of the impact test samples which were cut from the welded plates:

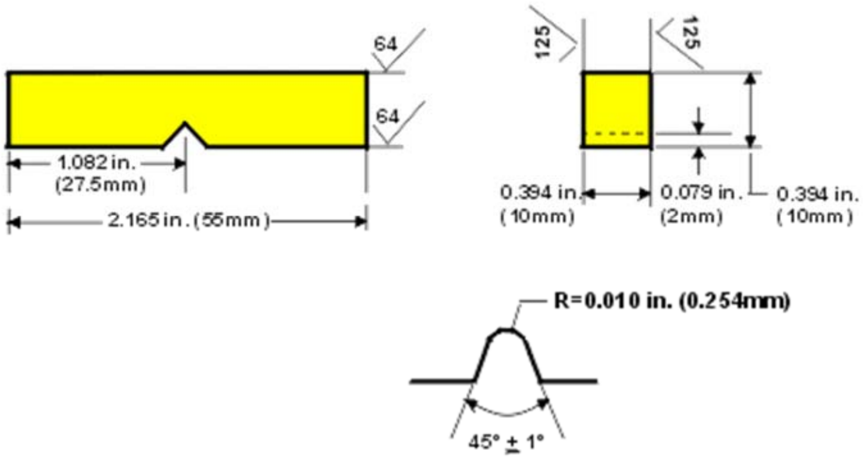


Figure 26: Impact toughness test specimen design [52]

The length of the welded area allowed for 7 samples to be cut from a single welded plate. This was found to be a sufficient number of samples to get a good average result. These samples would be tested using the Charpy Impact testing machine. The Charpy Impact testing machine samples cut from the main welded plate are shown in Figures 27 and 28:

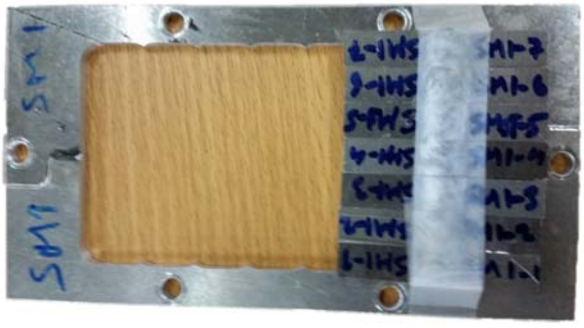


Figure 27: Welded plate toughness specimens cut

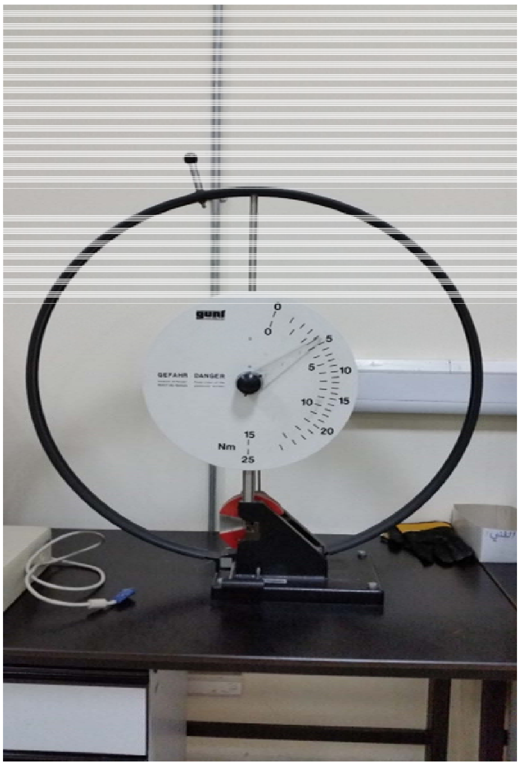


Figure 28: Charpy impact testing machine

Each of the specimens cut from this plate was given a suffix to help trace the sample from which the specimen was cut. The nomenclature would also identify the location of the specimen along the weld length. Figure 29 and Table 13 explain the nomenclature:

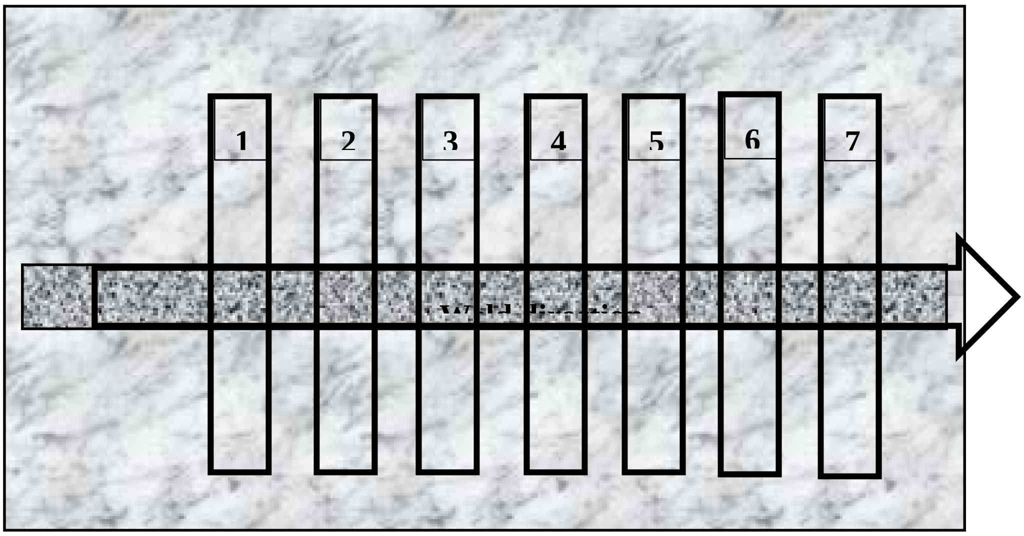


Figure 29: Impact toughness test specimen approximate locations

Table 13: Impact toughness specimens nomenclature

| Process | Sample name | Suffix |
|---|---|---|
| GTAW | STX- | Location of specimen (1, 2, 3, etc.) |
| GMAW | SMX- | Location of specimen (1, 2, 3, etc.) |
| FSW | SFX- | Location of specimen (1, 2, 3, etc.) |

For example, a specimen with the name SM3-5 belongs to the third trial of GMAW at the fifth location of the impact test specimens. Identifying the location might help justify abnormal results later on in the discussion stage. The first and last specimens are expected to be abnormally low due improper weld process initialization and completion. The testing was repeated for all samples, and all the data was recorded for further sustainability analysis. An impact test specimen is shown in Figure 30 after the tests have been completed:

Figure 30: Impact testing specimen after testing

## 3.4. Experimental Results

The case study results are discussed in this section. These results output the indicator values which then were used for the sustainability assessment. The individual indicators were discussed first with a comparison of the values between the three processes. Then the results were summarized for each process before applying the indicator values to the equations and obtaining the sustainability performance scores.

**3.4.1. Yield strength.** The yield strength is an indicator which belongs to the physical performance category. The values were obtained by testing the yield strength samples in the tensile testing machine as previously discussed. The machine recorded load and extension values and output them for further processing. These values were manipulated to calculate the stress and strain values, and then these values were plotted on stress - strain curves. Figure 31 shows the stress strain curves for the welded specimens:

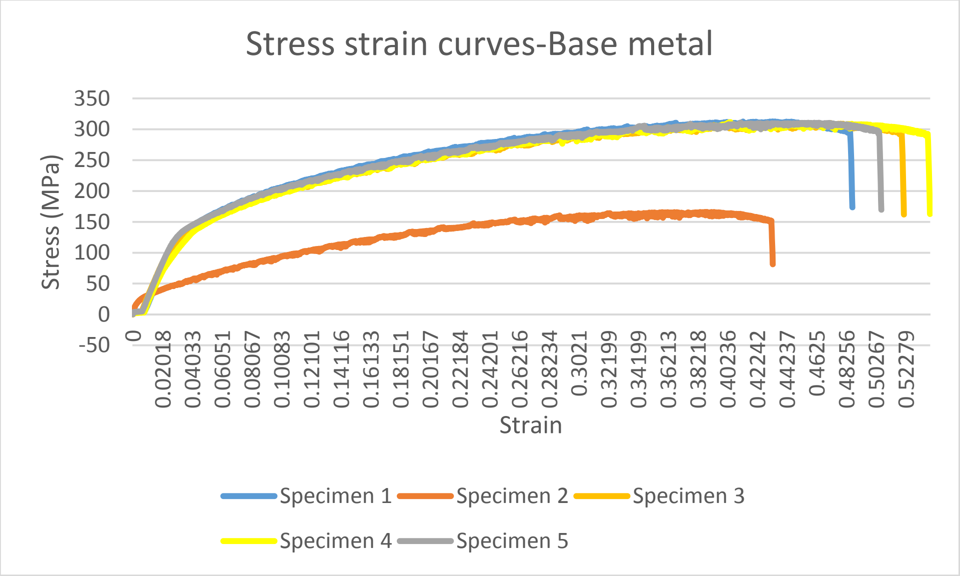


Figure 31: Base metal stress strain curves

Similar curves were prepared for each specimen result, and the yield strength was obtained from the graph and recorded. To come to a conclusive value for each welding process, the average between all specimens was taken as a representative. Some values were considered outliers, and were in turn not taken into consideration when calculating the average value. The yield strength results are summarized in Table 14:

Table 14: GTAW tensile test results

| Specimen | Yield Strength (MPa) | Remarks |
|---|---|---|
| ST2-1 | 51.3 | |
| ST2-2 | 51.9 | |
| ST2-3 | 38.1 | |
| ST2-4 | 62.0 | |
| ST2-5 | 44.3 | |
| TIG AVG | 49.5 | Taken as the yield strength value |

The specimens for GTAW displayed a wide spread of values. Thus, none of the values were considered outliers in this case, even with the lack of precision. This is mainly due to the quality of the weld as this weld is highly dependent on the welder’s craftsmanship, and the operating conditions during the weld.

Table 15: GMAW tensile test result

| Specimen | Yield Strength (MPa) | Remarks |
|---|---|---|
| SM3-1 | 38.9 | |
| SM3-2 | 50.1 | |
| SM3-3 | 55.7 | |
| SM3-4 | 43.9 | |
| SM3-5 | 53.0 | |
| MIG AVG | 48.3 | Taken as the yield strength value |

The specimens for GMAW were a little more precise. However, it should be noted that specimen 1 and 4 were low. The first specimen could be justified by welding startup, but the reason for fourth could only be poor weld quality.

Table 16: FSW tensile test result

| Specimen | Yield Strength (MPa) | Remarks |
|---|---|---|
| SF6-1 | 94.2 | |
| SF6-2 | 112.8 | |
| SF6-3 | 109.2 | |
| SF6-4 | 100.2 | |
| SF6-5 | 69.9 | Outlier, not taken into consideration |
| FSW AVG | 104.1 | Taken as the yield strength value |

Apart from the last specimen in FSW, the values for this process were a lot closer than the other processes. The fifth specimen was very far from the other values and therefore was considered as an outlier.

Table 17: Base material tensile test results

| Specimen | Yield Strength (MPa) | Remarks |
|---|---|---|
| SB-1 | 144.5 | |
| SB-2 | 22.3 | Outlier, not taken into consideration |
| SB-3 | 123.7 | |
| SB-4 | 140.5 | |
| SB-5 | 132.7 | |
| BASE AVG | 112.74 | Taken as the yield strength value |

Apart from the second specimen, the rest of the specimen values were close. Therefore, the second specimen was considered as an outlier.

The obtained average values for each process were compared in the bar chart below. As can be seen, the arc welding processes have performed significantly lower than FSW. However, all processes have resulted in a yield strength which is lower than the base metal. This means that the sustainability score for this particular indicator should be relatively low, with FSW having the highest value.

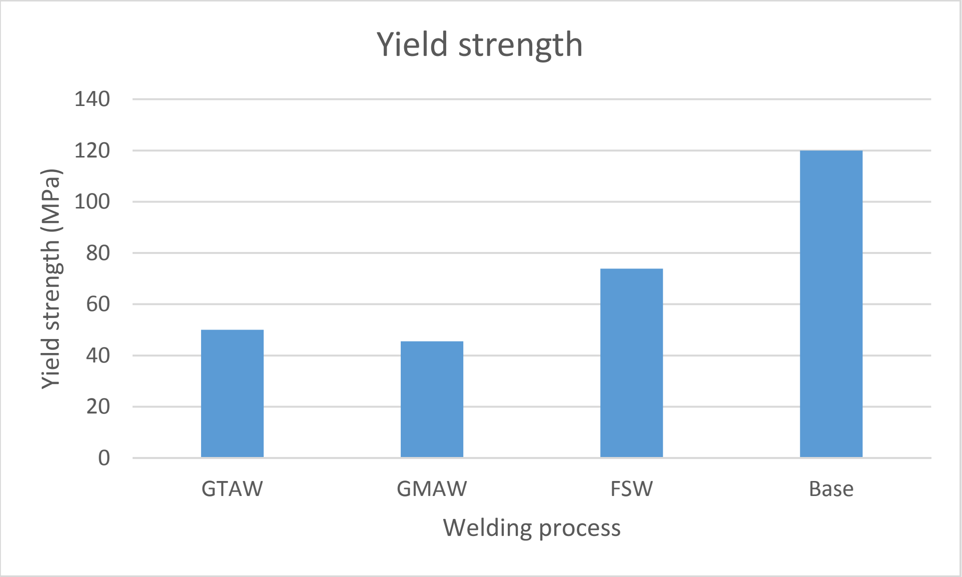


Figure 32: Yield strength comparison

**3.4.2. Impact toughness.** The impact toughness is an indicator which belongs to the physical performance category. The value was measured by testing the impact toughness specimens. The machine friction would be taken into account by measuring it and then deducting the friction amount from all toughness values from the specimens. Table 18 summarizes the findings of the impact toughness tests:

Table 18: GTAW impact test results

| Specimen | Energy (J) | Friction (J) | Toughness (J) | Remarks |
|---|---|---|---|---|
| ST3-1 | 2.1 | 1.8 | 0.3 | |
| ST3-2 | 2.2 | 1.8 | 0.4 | |
| ST3-3 | 2.5 | 1.8 | 0.7 | |
| ST3-4 | 2.2 | 1.8 | 0.4 | |
| ST3-5 | 2.2 | 1.8 | 0.4 | |
| ST3-6 | 2.2 | 1.8 | 0.4 | |
| ST3-7 | 2.2 | 1.8 | 0.4 | |
| TIG AVG | 2.2 | 1.8 | 0.4 | Taken as the impact toughness value |

The values for GTAW are surprisingly low. However, the results are precise and none of the values was considered as an outlier.

Table 19: GMAW impact test result

| Specimen | Energy (J) | Friction (J) | Toughness (J) | Remarks |
|---|---|---|---|---|
| SM1-1 | 2 | 1.8 | 0.2 | |
| SM1-2 | 2.1 | 1.8 | 0.3 | |
| SM1-3 | 2.1 | 1.8 | 0.3 | |
| SM1-4 | 2.2 | 1.8 | 0.4 | |
| SM1-5 | 2.3 | 1.8 | 0.5 | |
| SM1-6 | Fail | | | Sample failed |
| SM1-7 | 2.1 | 1.8 | 0.3 | |
| MIG AVG | 2.1 | 1.8 | 0.3 | Taken as the impact toughness value |

The GMAW toughness values are again low, but also with the values relatively close to each other. The toughness value for specimen 6 could not be recorded due to technical issues while taking the measurement.

Table 20: FSW impact test results

| Specimen | Energy (J) | Friction (J) | Toughness (J) | Remarks |
|---|---|---|---|---|
| SF7-1 | 3.8 | 1.8 | 2 | |
| SF7-2 | 3.8 | 1.8 | 2 | |
| SF7-3 | 3.4 | 1.8 | 1.6 | |
| SF7-4 | 3.3 | 1.8 | 1.5 | |
| SF7-5 | 3.4 | 1.8 | 1.6 | |
| SF7-6 | 3.2 | 1.8 | 1.4 | |
| SF7-7 | 3.8 | 1.8 | 2 | |
| FSW 7 AVG | 3.5 | 1.8 | 1.7 | Same result for both FSW samples |
| SF9-1 | 3.4 | 1.8 | 1.6 | |
| SF9-2 | 3 | 1.8 | 1.2 | |
| SF9-3 | 3.1 | 1.8 | 1.3 | |
| SF9-4 | 3.3 | 1.8 | 1.5 | |
| SF9-5 | 3.4 | 1.8 | 1.6 | |
| SF9-6 | 3.6 | 1.8 | 1.8 | |
| SF9-7 | 4.6 | 1.8 | 2.8 | |
| FSW 9 AVG | 3.5 | 1.8 | 1.7 | Same result for both FSW samples |

The FSW specimens show a higher value than the arc welding ones, but still considered to be low. Two FSW samples were tested to get a confident result. The same average value was obtained for all samples.

Table 21: Base material impact test result

| Specimen | Energy (J) | Friction (J) | Toughness (J) | Remarks |
|---|---|---|---|---|
| SB-1 | 11.8 | 1.8 | 10 | |
| SB-2 | 11.6 | 1.8 | 9.8 | |
| SB-3 | 11.9 | 1.8 | 10.1 | |
| SB-4 | Fail | | | Samples failed |
| SB-5 | 11.4 | 1.8 | 9.6 | |
| SB-6 | 12.2 | 1.8 | 10.4 | |
| BASE AVG | 11.8 | 1.8 | 10.0 | Taken as the impact toughness value |

The base metal values obtained were significantly higher. The base metal values are also close with the presence of one sample which had failed. This was again due to technical issues while taking the reading.

Comparing the performance of the welding processes with the base metal yields a very surprising result. The difference between the base metal and the welded specimens is quite significant. This is mainly due to having the welded section of the specimen more brittle than the base metal. The specimens do not have a yielded section, and instead shattered on impact. Combined with the lower yield strength result from the previous indicator, it helps provide an explanation to these numbers. In spite of that, FSW maintains the best toughness values. Figure 33 illustrates the average toughness values against the base metal values.

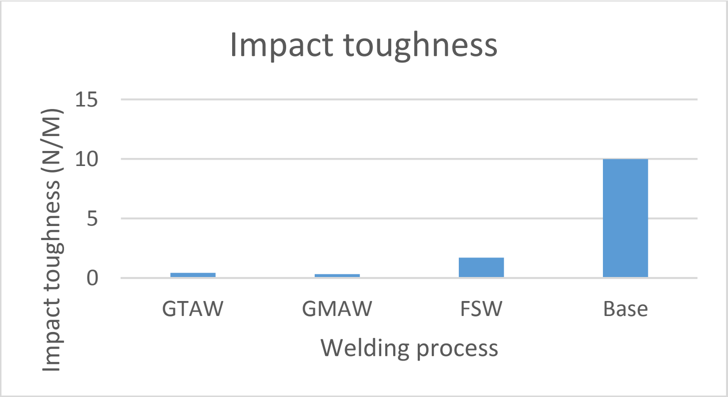


Figure 33: Impact toughness comparison

**3.4.3. Welding emissions.** The welding emissions indicator is an environmental impact indicator. This indicator was calculated by first calculating the mass of filler which was not transferred into the weld. The masses were measured using a balance.

$$mass_{wasted} = mass_{plate} + mass_{filler} - mass_{welded\ plate} \tag{12}$$

The value obtained for the mass wasted is then substituted in Equation 5 to get the amount of welding emissions generated. For an aluminum welding process, these typically include:

- Aluminum
- Silicon
- Copper
- Magnesium
- Manganese
- Chromium
- Zirconium
- Vanadium

Typically, the three fume producing welding processes are FCAW, SMAW, and GMAW. The rest of the welding processes produces a negligible amount of fumes [53]. The amount of fumes is detailed in Table 22:

Table 22: Welding process fumes [53]

| Welding process | Metal Type | Range of fumes (%) |
|---|---|---|
| FCAW | Carbon steel | 0.9-2.4 |
| | Stainless steel | 0.9-2.4 |
| SMAW | Carbon steel | 1.1-5.4 |
| | Stainless, high alloy | 0.3-1.4 |
| GMAW | Carbon steel | 0.3-0.9 |
| | Stainless Steel | 0.6-7 |
| | Copper/Aluminum | 0.5-1.6 |

Figure 34 shows the emission values compared between all three processes. Out of all processes, GMAW was the only process where weld emissions were detected and measured, as expected and within the range. GMAW and FSW did not show any mass wasted due to emissions and therefore should have an advantage in this area over GMAW.

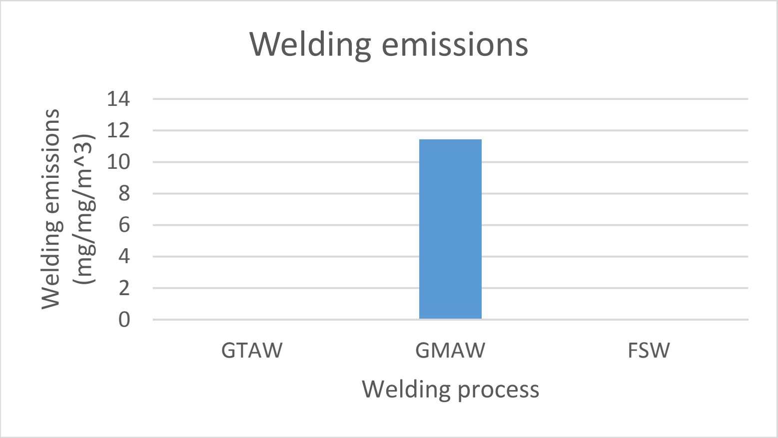


Figure 34: Weld emission comparison

**3.4.4. CO2 emissions.** CO2 emissions is an environmental impact indicator. CO2 emissions are associated with the carbon footprint of each process. This is obtained by measuring the amount of energy consumed during the process and comparing it with the allowable CO2 emission limit for the particular duration of each process. In the UAE each kWh of energy consumed produces 0.5 kg of CO2. The limit for CO2 emissions for industrial processes is 5000 kg/month. [54]

First the CO2 emission limit were determined for each process depending on the welding time. Then the CO2 emissions produced in the process will be calculated using Equation 6. The results of these calculations are shown in Figure 35:

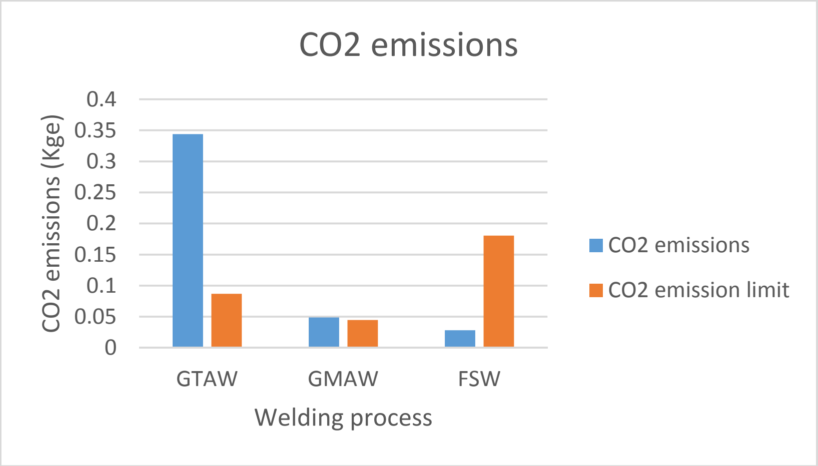


Figure 35: CO2 emissions comparison

It can be easily deduced that FSW was the best performer in this category. This is perhaps due to using a CNC machine which has been designed and developed to be energy efficient. GMAW slightly exceeded the limit and therefore would suffer. GTAW emissions were much more than the limit. This means the GTAW environmental score is expected to suffer significantly as compared to the other two processes.

**3.4.5. Auxiliary material.** Auxiliary material is an environmental impact indicator. Auxiliary material is used in welding processes to shield the hot weld from the atmosphere to prevent corrosion. This amount was measured, and then compared with the recommended maximum amount of auxiliary material to be used for welding, 9.87 L/min [55] for GTAW and 14.1 L/min [56] for GMAW. In the case of the FSW, the process does not require any auxiliary material. The comparisons are illustrated in Figure 36:

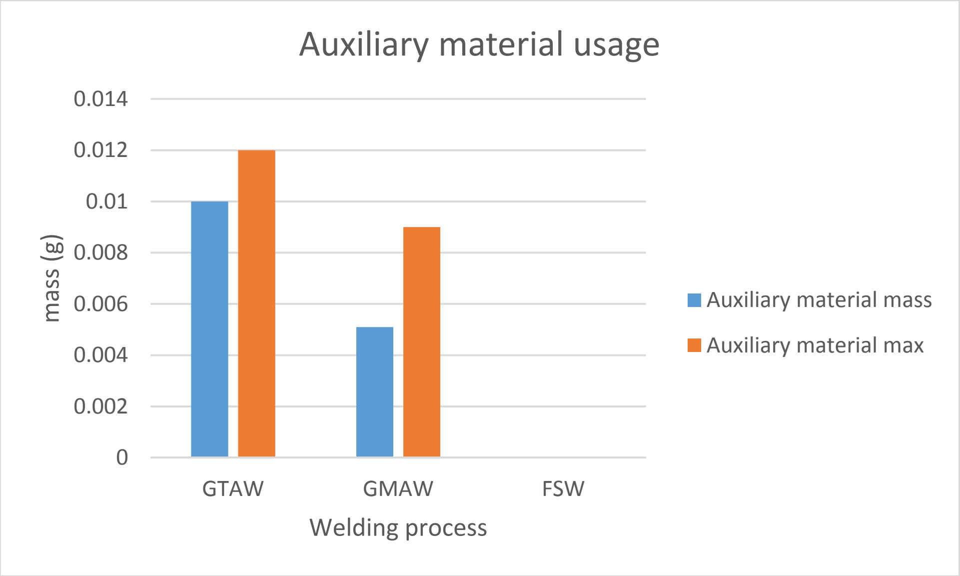


Figure 36: Auxiliary material usage comparison

From the bar chart, the conclusion that can be drawn is that the amount of auxiliary material used for shielding in arc welding processes in this experiment is less than the maximum amount. This means that there was no excess that was wasted. However, when the arc welding processes are compared to FSW which used no auxiliary material, the final category score would definitely be impacted.

**3.4.6. Material wasted.** Material wastage is an environmental impact indicator. It was measured by finding the difference between the masses of the un-welded plates with the filler mass consumed, and the mass of plates after welding. The same equation used previously to calculate the mass wasted was applied again. In the specifics of this experiment, the wasted mass was negligible and therefore would not contribute to the environmental impact. However, this does not imply that all welding processes would have this outcome. This indicator should continue to be part of the methodology and applied when appropriate.

**3.4.7. Labor cost.** Labor cost is an economic impact indicator. In this case study experiment, all processes were performed by the same person. Therefore, the cost of labor was taken to be the same per unit of time for each process. This rate could then be multiplied by the welding time to get the labor cost for each process.

However, to simulate a real scenario, adjustments were made to the rate relative to the level of difficulty of each welding process. This was done to reflect the different skill level of the welder performing the process and adjusting the rate as applicable. In the case of FSW, a machinist rate will be taken. These rates have been deduced from industry rates, change to AED/min, and are compared in Figure 37:

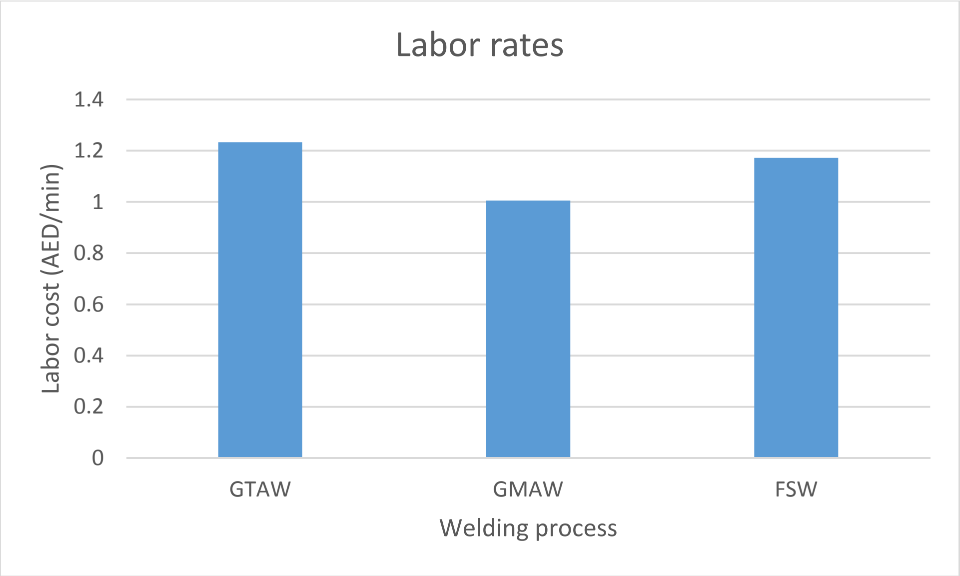


Figure 37: Welding labor rates comparison [57] [58]

Even though the rates may appear to be somewhat close, it must be declared that GMAW has the cheapest labor, followed by FSW, and then GTAW is the most expensive. This is expected due to the fact that GMAW is the easiest among the arc welding processes. The rate for FSW was taken as that for a CNC machinist. This would explain why it would be relatively high as compared with a manual process. Computerized manufacturing does take a little bit of extra effort to input the program into the machines.

**3.4.8. Weld time.** Welding time is an economic impact indicator. It was measured during the experiment as accurately as possible. The measured times for the processes are shown in Figure 38:

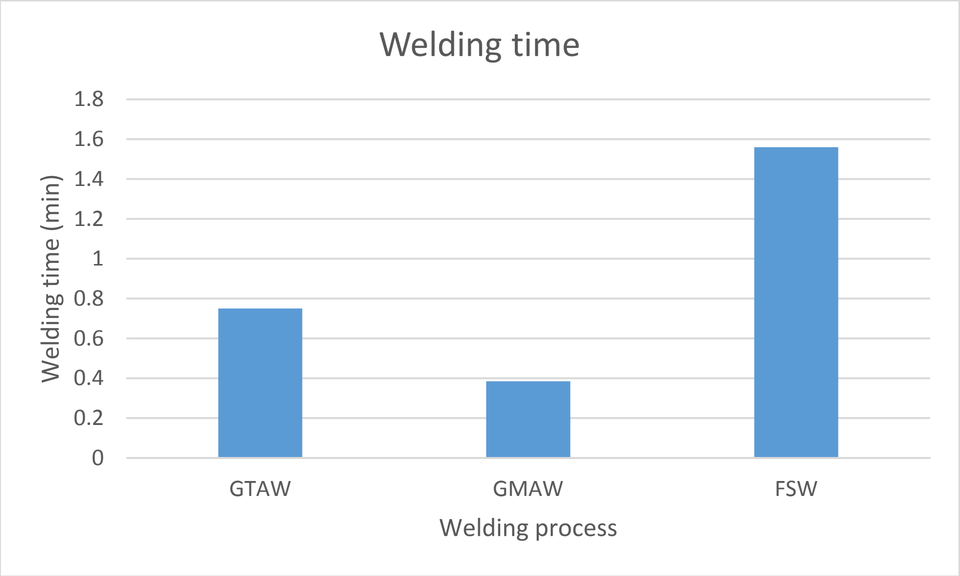


Figure 38: Welding time comparison

GMAW is the fastest process followed by GTAW. FSW took longer than the arc welding processes because the welding process itself is slower. Moreover, a hole needs to be drilled before the actual welding can start.

**3.4.9. Consumable cost.** Cost is usually split into capital and operational cost. They should be both considered where applicable, however, in this experiment the capital cost was not considered for the processes as it would be negligible. The operational cost was calculated from the consumable cost.

For arc welding processes, the actual welding equipment has such a long life that it would be negligible when compared to the filler cost used. Thus, for arc welding processes, the capital cost was neglected and only the consumable cost was considered. On the other hand, FSW does not use a consumable per se. This leads to using the FSW tool cost as the consumable cost. The FSW tool cost is calculated using the given tool life cycle, and multiplying the tool cost by the ratio of the welding length to the tool life length. The tool life for the particular FSW tool used at the particular conditions was found to be 2000m [59]. The calculation was done as shown in Equation 13:

$$FSW_{cost} = cost_{tool} * \frac{length_{weld}}{length_{tool\,life}} \tag{13}$$

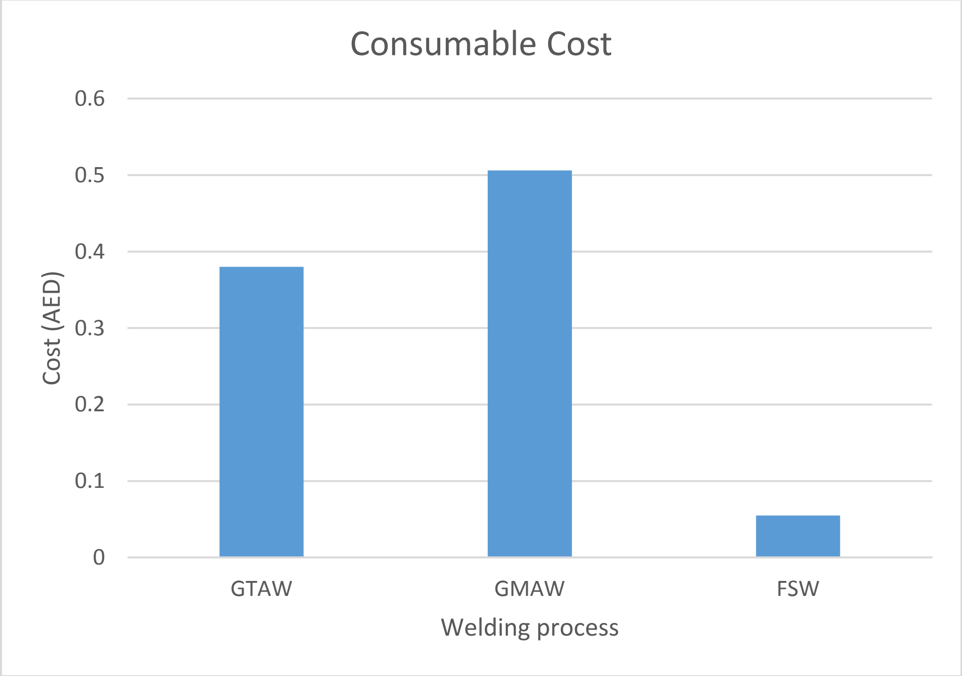


Figure 39: Consumable cost comparison

FSW has clearly bested the competing processes by achieving a very low cost. This is expected given the long tool life of the FSW tool. It is always expected that capital cost would always be less than running cost when divided on the total lifetime. GTAW was the second cheapest, and GMAW was the most expensive.

**3.4.10. Energy cost.** Energy cost is an economic impact indicator. The energy consumption was measured during the experiment using a Power Sight power consumption measurement device connected to a computer. This was then multiplied by the kWh rate, 0.23AED/kWh [54], to obtain the cost.

GTAW energy consumption was large due to the particular process requirements. GMAW had more reasonable consumption, and FSW had the least energy consumption.

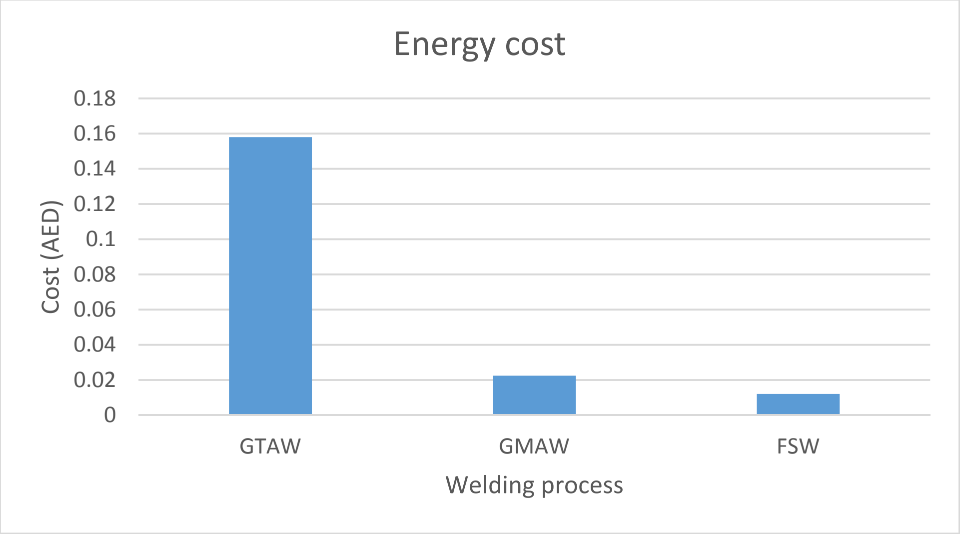


Figure 40: Energy cost comparison

**3.4.11. Total cost.** To get an overview of the total cost, the aforementioned costs were added and plotted on the bar chart below. As an indicator of the costs, the total cost was compared to the total plate cost. This should give an indicator of what ratio of the cost of the plate was needed to perform the welds.

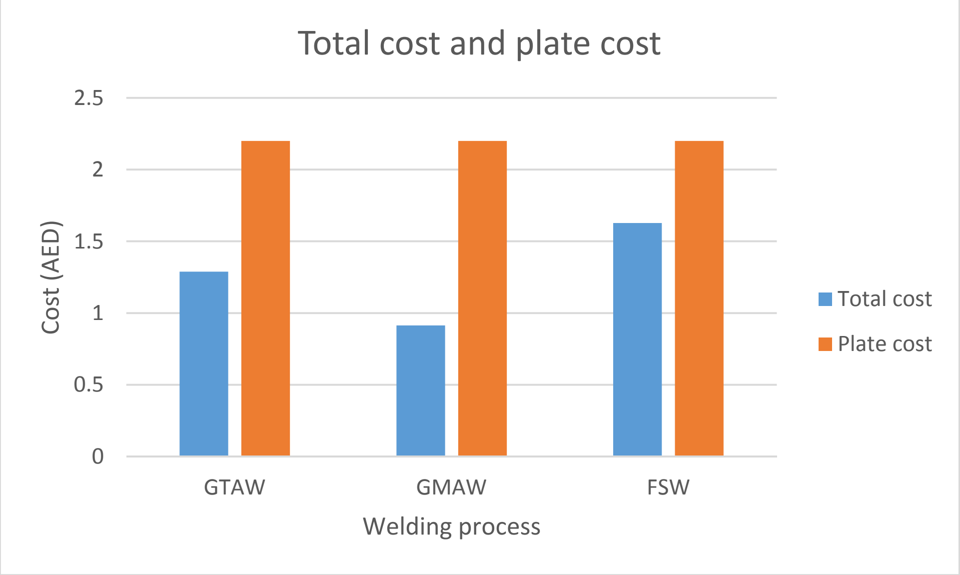


Figure 41: Total cost of welding vs cost of plate

As can be seen, none of the processes exceeded the original plate cost. However, FSW was the overall most expensive process. It was followed by GTAW, and GMAW was the cheapest process.

**3.4.12. Incident rate.** To quantify the social impact category score, the incident rates were obtained and compared for each process. For both arc welding processes, the incident rate was taken for welding, but for FSW the incident rate was considered as that of machining. The incident rates were obtained from annual reports by the Bureau of Labor Statistics (BLS) for each of the occupations. [60] To make the indicator non-dimensional, the rates were divided by the maximum incident rate of manufacturing processes for each respective year. The values are shown in the bar chart in Figure 42:

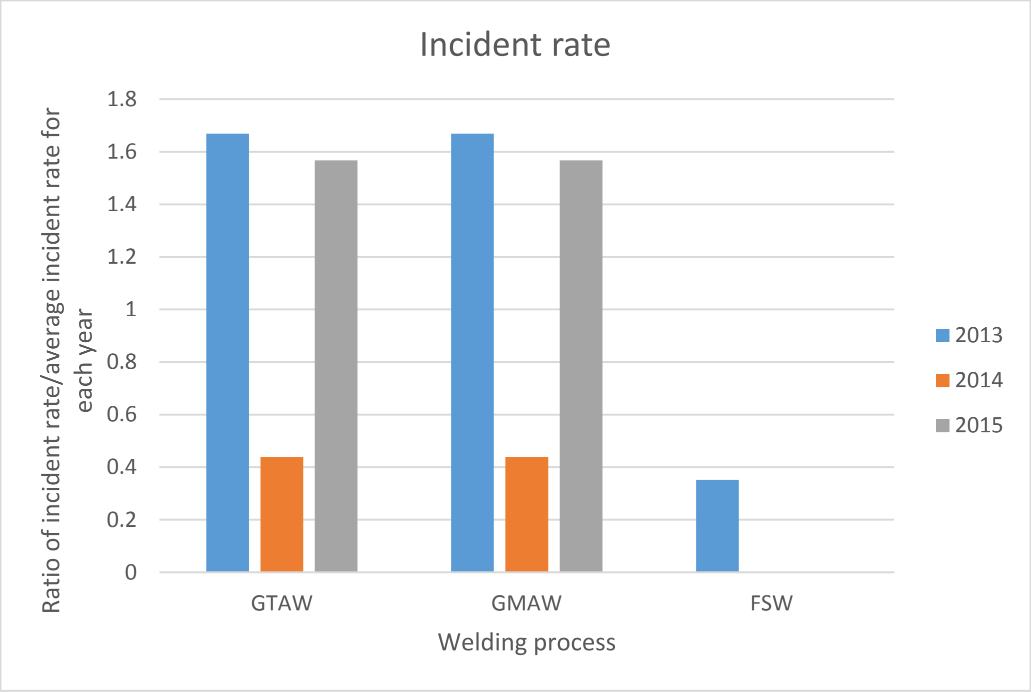


Figure 42: Incident rate comparison

Due to the reduced risks of FSW, it should be no surprise that the incident rate for that process is much lower than arc welding. This is due to less heat exposure, welding fume exposure, manual labor required, etc. On the other hand, arc welding incident ratios were higher than 1 in 2013 and 2015. This indicates that not only is arc welding dangerous, but it is a main contributor to increasing the incident rate.

After comparing the results of each of the indicators for all three processes, the category scores for the processes were compiled and discussed.

**3.4.13. GTAW Results.** Category score for GTAW is low. However, when compared to the other two processes, it is not the worst performer. Culminating the yield strength and the impact toughness gives it the second ranking among the processes, and the top rank in the arc welding processes. This shows that GTAW does indeed perform well physically regardless of the other category scores.

Table 23: GTAW physical performance results

| Physical performance | | | |
|---|---|---|---|
| Yield strength of welded specimen (MPa) | Yield strength of base metal (MPa) | Charpy impact toughness of welded specimen (Nm) | Charpy impact toughness of base metal (Nm) |
| 50.02 | 120 | 0.43 | 9.98 |
| Category total = 0.23 | | | |

Table 24: GTAW environmental impact results

| Environmental impact | | | | | | |
|---|---|---|---|---|---|---|
| Welding emissions (g/m^3) | CO2 footprint (kg) | CO2 footprint limit (kg) | Auxiliary material used (g) | Auxiliary material max (g) | Material wastage (g) | Weld mass (g) |
| 0 | 0.344 | 0.0868 | 0.01 | 0.012 | 0 | 4 |
| Category total = 0 (actual score was negative) | | | | | | |

Since there was no material wastage, metal emissions were not available, which is a good outcome from the process. However, due to the massive power consumption of the process, the carbon footprint is much higher that the limit. Therefore, the score dropped drastically making this process by far the worst performing environmentally.

Table 25: GTAW economic impact results

| Economic impact | | | | | | | |
|---|---|---|---|---|---|---|---|
| Weld time (min) | Labor cost (AED /min) | Consumable cost (AED/g) | Equipment cost (AED/m) | Energy consumption (kW) | Energy consumption cost (AED) | Plate mass (g) | Cost of plate (AED/g) |
| 0.75 | 1.23 | 0.38 | 0 | 0.688 | 0.158 | 200 | 0.011 |
| Category total = 0.335 | | | | | | | |

Overall, the cost of the process is reasonable with the exception of the energy consumption cost. It is relatively higher than the other processes due to a higher power consumption. Economically it ranked second among the three processes which is reasonable, however, it was the more expensive option between the arc welding processes.

Table 26: GTAW social impact results

| Social impact | | |
|---|---|---|
| Incident rate 2013 (days away from work/10,000 employees) | Incident rate 2014 (days away from work/10,000 employees) | Incident rate 2015 (days away from work/10,000 employees) |
| 182.6 (compared to 301.7 for construction labor) [61] | 47 (compared to 309.7 for construction labor) [62] | 163 (compared to 289.9 for sheet metal working) [60] |
| Category total = 0.5602 | | |

These figures represent the BLS incident rates for welders. These have been taken for the last two reports produced. This was done because the rate seems to be dropping with time due to possible increases in safety measures. Both arc welding processes would have the same scores. The arc welding scores would be worse than FSW, as these processes seem safer.

**3.4.14. GMAW Results.** This welding process did have material wastage. The CO2 footprint was reasonable as well. Therefore, it is no surprise that this process performed better than GTAW. The only other factor that hindered its environmental impact is the use of shielding material.

Table 27: GMAW physical performance results

| Physical performance | | | |
|---|---|---|---|
| Yield strength of welded specimen (MPa) | Yield strength of base metal (MPa) | Charpy impact toughness of welded specimen (Nm) | Charpy impact toughness of base metal (Nm) |
| 45.52 | 120 | 0.33 | 9.98 |
| Category total = 0.206 | | | |

Table 28: GMAW environmental impact results

| Environmental impact | | | | | | |
|---|---|---|---|---|---|---|
| Welding emissions (g/m^3) | CO2 footprint (kg) | CO2 footprint limit (kg) | Auxiliary material used (g) | Auxiliary material limit (g) | Material wastage (g) | Weld mass (g) |
| 0.00817 | 0.0488 | 0.0446 | 0.0051 | 0.009 | 0 | 4.5 |
| Category total = 0.577 | | | | | | |

This welding process did have material wastage. The CO2 footprint was reasonable as well. Therefore, it is no surprise that this process performed better than GTAW. The only other factor that hindered its environmental impact is the use of shielding material.

Table 29: GMAW economic impact results

| Economic impact | | | | | | | |
|---|---|---|---|---|---|---|---|
| Weld time (min) | Labor cost (AED /min) | Consumable cost (AED/g) | Equipment cost (AED/m) | Energy consumption (kW) | Energy consumption cost (AED) | Plate mass (g) | Cost of plate (AED /g) |
| 0.385 | 1.01 | 0.506 | 0 | 0.0975 | 0.0224 | 200 | 0.011 |
| Category total = 0.584 | | | | | | | |

The cost of this process seems to be very low and is probably one of the reasons why GMAW is very widespread in the industry. It was the cheapest among the three processes by a good margin.

Table 30: GMAW social impact results

| Social impact | | |
|---|---|---|
| Incident rate 2013 (days away from work/10,000 employees) | Incident rate 2014 (days away from work/10,000 employees) | Incident rate 2015 (days away from work/10,000 employees) |
| 182.6 (compared to 301.7 for construction labor) [61] | 47 (compared to 309.7 for construction labor) [62] | 163 (compared to 289.9 for sheet metal working) [60] |
| Category total = 0.5602 | | |

These figures represent the BLS incident rates for welders. These have been taken for the last two reports produced. This was done because the rate seems to be dropping with time due to possible increases in safety measures. Both arc welding processes would have the same scores.

**3.4.15. FSW Results.** The physical performance of FSW is higher than that of the other two arc welding processes, but the impact toughness remains considerably lower than the base metal. Regardless of that, FSW scored the highest in physical performance.

Table 31: FSW physical performance results

| Physical performance | | | |
|---|---|---|---|
| Yield strength of welded specimen (MPa) | Yield strength of base metal (MPa) | Charpy impact toughness of welded specimen (Nm) | Charpy impact toughness of base metal (Nm) |
| 73.86 | 120 | 1.71 | 9.98 |
| Category total = 0.393 | | | |

Table 32: FSW environmental impact results

| Environmental impact | | | | | |
|---|---|---|---|---|---|
| Welding emissions (g/m^3) | CO2 footprint (kg) | CO2 footprint limit (kg) | Auxiliary material used (g) | Material wastage (g) | Weld mass (g) |
| 0 | 0.02805 | 0.181 | 0 | 0 | 5.4 |
| Category total = 0.9612 | | | | | |

This process seems to be very environmentally friendly. Due to the fact that no shielding was required, no emissions were produced, and the CO2 footprint was low, it is expected that this process scored exceptionally high.

Table 33: FSW economic impact results

| Economic impact | | | | | | | |
|---|---|---|---|---|---|---|---|
| Weld time (min) | Labor cost (AED/ min) | Consumable cost (AED/g) | Equipment cost (AED/m ) | Energy consumption (kW) | Energy consumption cost (AED) | Plate mass (g) | Cost of plate (AED /g) |
| 1.56 | 1.17 | 0 | 0.055 | 0.0561 | 0.012 | 200 | 0.011 |
| Category total = 0.139 | | | | | | | |

Economically, this process might not be the cheapest due to the high fixed cost of the special FSW tool. Its score determined that it was the most expensive of the 3 processes.

The incident statistics were taken from BLS incident rate reports. It should be noted that for FSW, the incident rates taken are the ones for machinists. FSW may be a welding process, but it is performed using a CNC milling machine, and therefore safety hazards should be similar to the ones for a machining process.

Table 34: FSW social impact results

| Social impact | | |
|---|---|---|
| Incident rate 2013 (days away from work/10,000 employees) | Incident rate 2014 (days away from work/10,000 employees) | Incident rate 2015 (days away from work/10,000 employees) |
| 38.5 (compared to 301.7 for construction labor) [61] | 0 [62] | 0 [60] |
| Category total = 0.9575 | | |

## 3.5. Survey Weights

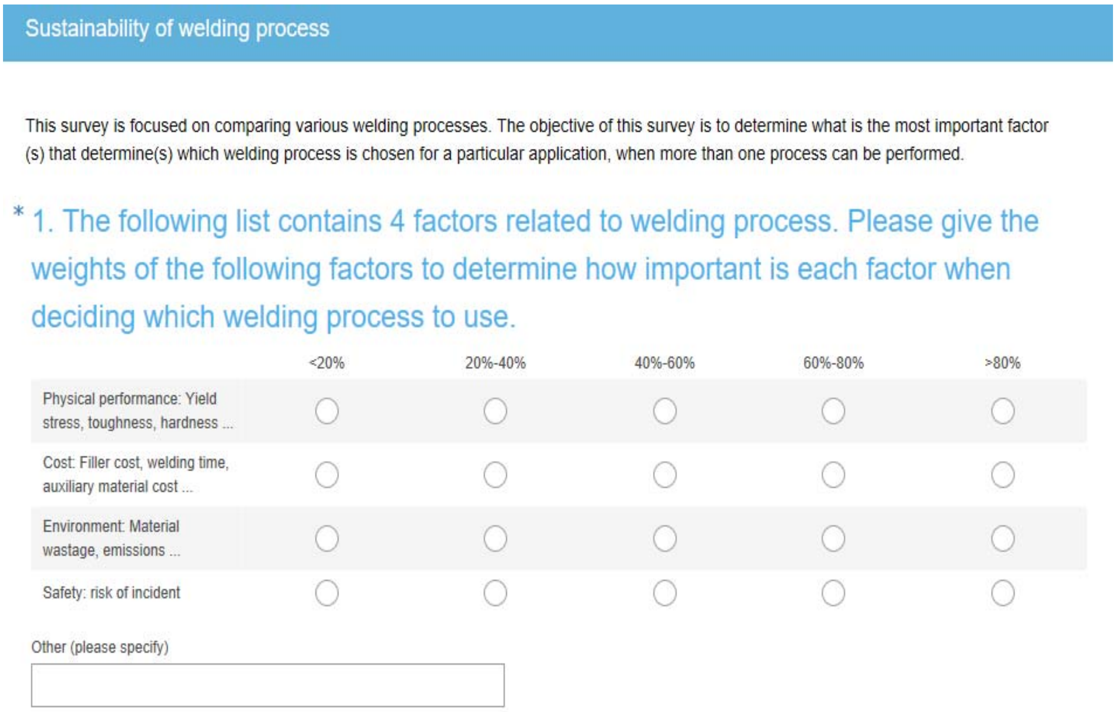
As mentioned in the methodology section, in order to aggregate the individual scores from all the categories into a single sustainability score, a weighted average method was used. These weights were obtained from a survey which was created and distributed to people with a wide variety of backgrounds. These include:

- Engineers
- Welders
- Professors
- Safety personnel
- Doctors
- Environmental personnel

This collection of people was chosen to eliminate bias towards any particular category. Furthermore, the participants were exclusively taken from welding and/or manufacturing backgrounds. The survey was kept very direct and simple in order to ease the recipients' answering process. Only two questions were asked in the survey since that is all that was needed. The questions are shown in Figures 44 and 45:

The first question was meant to help provide the weights which are used for aggregation. The results were collected and analyzed through taking a weighted average between the Reponses to get the category weights.

The second question was only meant to identify the population who received and responded to this survey.



Sustainability of welding process

This survey is focused on comparing various welding processes. The objective of this survey is to determine what is the most important factor (s) that determine(s) which welding process is chosen for a particular application, when more than one process can be performed.

* 1. The following list contains 4 factors related to welding process. Please give the weights of the following factors to determine how important is each factor when deciding which welding process to use.

| | <20% | 20%-40% | 40%-60% | 60%-80% | >80% |
|---|---|---|---|---|---|
| Physical performance: Yield stress, toughness, hardness ... | ○ | ○ | ○ | ○ | ○ |
| Cost: Filler cost, welding time, auxiliary material cost ... | ○ | ○ | ○ | ○ | ○ |
| Environment: Material wastage, emissions ... | ○ | ○ | ○ | ○ | ○ |
| Safety: risk of incident | ○ | ○ | ○ | ○ | ○ |

Other (please specify)

Figure 43: Weight survey question 1

* 2. Please describe your professional focus.

○ Welding engineering
○ Welding supervisor/superintendent
○ Professor
○ Environmental sector professional
○ Other (please specify)

Figure 44: Weight survey question 2

After the distribution of the survey to a number of individuals, the weights were collected and analyzed. In order to receive fair results, the survey was given to nearly an equal amount of engineers/professors/welders and doctors/environmental personnel/safety personnel. Table 35 below shows the number of participants and their professional affiliations:

Table 35: Number of participants in survey

| Total number of participants | 45 |
|---|---|
| Number of engineers/welders/professors | 23 |
| Number of doctors/environmental/safety personnel | 22 |

Arguably, the number of participants in the survey may be deemed as low. In statistically terms, the sample size is considerably lower than the hypothesized size of the population, which in this case is represented by everyone affiliated with welding and manufacturing who may have been able to participate meaningfully in the survey. Nevertheless, the outcome implied that the results are trustworthy, but to numerically prove that the sample size taken sufficient to draw a conclusion, a simple statistical study was run. The sample mean weights, sample standard deviation, and sample standard error for each of the categories was determined. This was then used along with the standard T distribution values to find the upper and lower confidence limits at a 95% level of confidence. The T distribution is shown Figure 45.

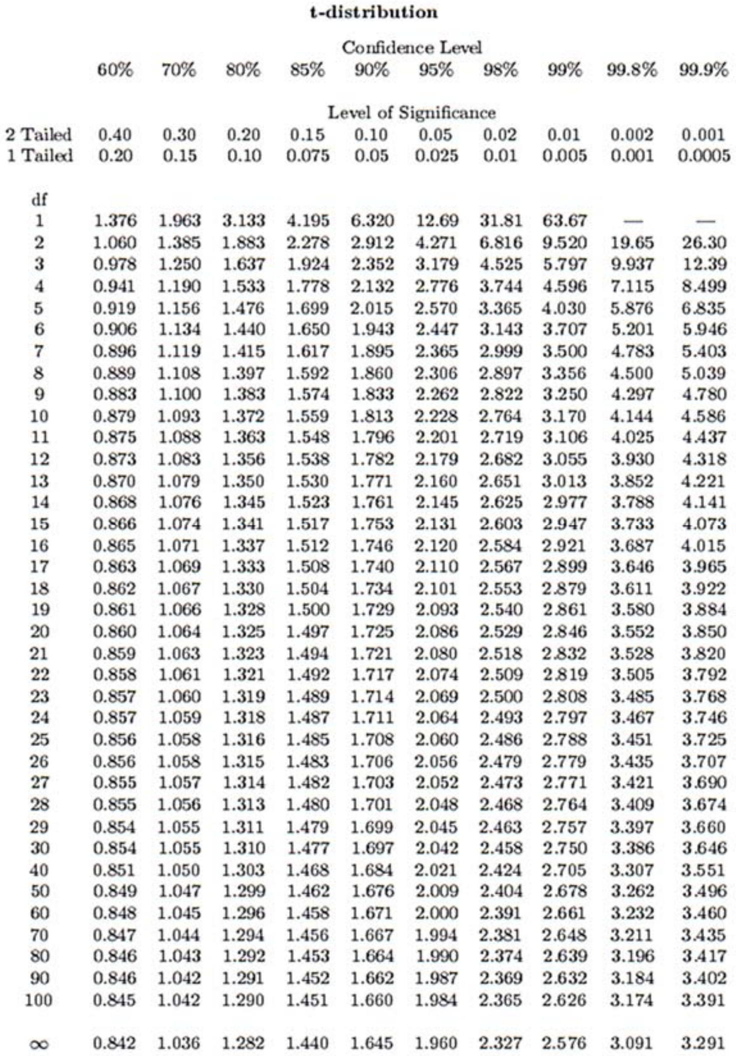
Standard statistical studies typically use 90%, 95%, or 99% confidence levels. 95% was chosen for this study as a compromise so as neither to take the lowest confidence level and overestimate the result, nor to take the highest and underestimate the result [63]. The equations used to determine and the resulting values are stated in Equations 14, 15, and 16:

$$Standard\ sample\ error = \frac{Sample\ standard\ deviation}{\sqrt{Number\ of\ participants - 1}}\ [63] \tag{14}$$

$$Upper\ confidence\ limit = mean + T * Standard\ sample\ error\ [63] \tag{15}$$

$$Lower\ confidence\ limit = mean - T * Standard\ sample\ error\ [63] \tag{16}$$

Typically, as the number of participants increase for the survey, the value of T decreases, which narrows the confidence level gap. To numerically prove that the number of participants is good enough to continue with the study, the values obtained for the T value at sample size of 45 were compared to the values for the minimum possible T, corresponding to the sample size of beyond 100.



**t-distribution**

Confidence Level

Level of Significance

| | 60% | 70% | 80% | 85% | 90% | 95% | 98% | 99% | 99.8% | 99.9% |
|---|---|---|---|---|---|---|---|---|---|---|
| 2 Tailed | 0.40 | 0.30 | 0.20 | 0.15 | 0.10 | 0.05 | 0.02 | 0.01 | 0.002 | 0.001 |
| 1 Tailed | 0.20 | 0.15 | 0.10 | 0.075 | 0.05 | 0.025 | 0.01 | 0.005 | 0.001 | 0.0005 |
| df | | | | | | | | | | |
| 1 | 1.376 | 1.963 | 3.133 | 4.195 | 6.320 | 12.69 | 31.81 | 63.67 | — | — |
| 2 | 1.060 | 1.385 | 1.883 | 2.278 | 2.912 | 4.271 | 6.816 | 9.520 | 19.65 | 26.30 |
| 3 | 0.978 | 1.250 | 1.637 | 1.924 | 2.352 | 3.179 | 4.525 | 5.797 | 9.937 | 12.39 |
| 4 | 0.941 | 1.190 | 1.533 | 1.778 | 2.132 | 2.776 | 3.744 | 4.596 | 7.115 | 8.499 |
| 5 | 0.919 | 1.156 | 1.476 | 1.699 | 2.015 | 2.570 | 3.365 | 4.030 | 5.876 | 6.835 |
| 6 | 0.906 | 1.134 | 1.440 | 1.650 | 1.943 | 2.447 | 3.143 | 3.707 | 5.201 | 5.946 |
| 7 | 0.896 | 1.119 | 1.415 | 1.617 | 1.895 | 2.365 | 2.999 | 3.500 | 4.783 | 5.403 |
| 8 | 0.889 | 1.108 | 1.397 | 1.592 | 1.860 | 2.306 | 2.897 | 3.356 | 4.500 | 5.039 |
| 9 | 0.883 | 1.100 | 1.383 | 1.574 | 1.833 | 2.262 | 2.822 | 3.250 | 4.297 | 4.780 |
| 10 | 0.879 | 1.093 | 1.372 | 1.559 | 1.813 | 2.228 | 2.764 | 3.170 | 4.144 | 4.586 |
| 11 | 0.875 | 1.088 | 1.363 | 1.548 | 1.796 | 2.201 | 2.719 | 3.106 | 4.025 | 4.437 |
| 12 | 0.873 | 1.083 | 1.356 | 1.538 | 1.782 | 2.179 | 2.682 | 3.055 | 3.930 | 4.318 |
| 13 | 0.870 | 1.079 | 1.350 | 1.530 | 1.771 | 2.160 | 2.651 | 3.013 | 3.852 | 4.221 |
| 14 | 0.868 | 1.076 | 1.345 | 1.523 | 1.761 | 2.145 | 2.625 | 2.977 | 3.788 | 4.141 |
| 15 | 0.866 | 1.074 | 1.341 | 1.517 | 1.753 | 2.131 | 2.603 | 2.947 | 3.733 | 4.073 |
| 16 | 0.865 | 1.071 | 1.337 | 1.512 | 1.746 | 2.120 | 2.584 | 2.921 | 3.687 | 4.015 |
| 17 | 0.863 | 1.069 | 1.333 | 1.508 | 1.740 | 2.110 | 2.567 | 2.899 | 3.646 | 3.965 |
| 18 | 0.862 | 1.067 | 1.330 | 1.504 | 1.734 | 2.101 | 2.553 | 2.879 | 3.611 | 3.922 |
| 19 | 0.861 | 1.066 | 1.328 | 1.500 | 1.729 | 2.093 | 2.540 | 2.861 | 3.580 | 3.884 |
| 20 | 0.860 | 1.064 | 1.325 | 1.497 | 1.725 | 2.086 | 2.529 | 2.846 | 3.552 | 3.850 |
| 21 | 0.859 | 1.063 | 1.323 | 1.494 | 1.721 | 2.080 | 2.518 | 2.832 | 3.528 | 3.820 |
| 22 | 0.858 | 1.061 | 1.321 | 1.492 | 1.717 | 2.074 | 2.509 | 2.819 | 3.505 | 3.792 |
| 23 | 0.857 | 1.060 | 1.319 | 1.489 | 1.714 | 2.069 | 2.500 | 2.808 | 3.485 | 3.768 |
| 24 | 0.857 | 1.059 | 1.318 | 1.487 | 1.711 | 2.064 | 2.493 | 2.797 | 3.467 | 3.746 |
| 25 | 0.856 | 1.058 | 1.316 | 1.485 | 1.708 | 2.060 | 2.486 | 2.788 | 3.451 | 3.725 |
| 26 | 0.856 | 1.058 | 1.315 | 1.483 | 1.706 | 2.056 | 2.479 | 2.779 | 3.435 | 3.707 |
| 27 | 0.855 | 1.057 | 1.314 | 1.482 | 1.703 | 2.052 | 2.473 | 2.771 | 3.421 | 3.690 |
| 28 | 0.855 | 1.056 | 1.313 | 1.480 | 1.701 | 2.048 | 2.468 | 2.764 | 3.409 | 3.674 |
| 29 | 0.854 | 1.055 | 1.311 | 1.479 | 1.699 | 2.045 | 2.463 | 2.757 | 3.397 | 3.660 |
| 30 | 0.854 | 1.055 | 1.310 | 1.477 | 1.697 | 2.042 | 2.458 | 2.750 | 3.386 | 3.646 |
| 40 | 0.851 | 1.050 | 1.303 | 1.468 | 1.684 | 2.021 | 2.424 | 2.705 | 3.307 | 3.551 |
| 50 | 0.849 | 1.047 | 1.299 | 1.462 | 1.676 | 2.009 | 2.404 | 2.678 | 3.262 | 3.496 |
| 60 | 0.848 | 1.045 | 1.296 | 1.458 | 1.671 | 2.000 | 2.391 | 2.661 | 3.232 | 3.460 |
| 70 | 0.847 | 1.044 | 1.294 | 1.456 | 1.667 | 1.994 | 2.381 | 2.648 | 3.211 | 3.435 |
| 80 | 0.846 | 1.043 | 1.292 | 1.453 | 1.664 | 1.990 | 2.374 | 2.639 | 3.196 | 3.417 |
| 90 | 0.846 | 1.042 | 1.291 | 1.452 | 1.662 | 1.987 | 2.369 | 2.632 | 3.184 | 3.402 |
| 100 | 0.845 | 1.042 | 1.290 | 1.451 | 1.660 | 1.984 | 2.365 | 2.626 | 3.174 | 3.391 |
| ∞ | 0.842 | 1.036 | 1.282 | 1.440 | 1.645 | 1.960 | 2.327 | 2.576 | 3.091 | 3.291 |

Figure 45: T distribution chart [64]

Table 36: Confidence limit values for sample of 45

| Category | Mean | Standard deviation | Standard sample error | Value of T | Upper confidence limit | Lower confidence limit |
|---|---|---|---|---|---|---|
| Physical performance | 0.297 | 0.073 | 0.011 | 2.01 | 0.319 | 0.274 |
| Economic impact | 0.241 | 0.088 | 0.013 | 2.01 | 0.268 | 0.215 |
| Environmental impact | 0.195 | 0.110 | 0.016 | 2.01 | 0.228 | 0.161 |
| Social impact | 0.267 | 0.111 | 0.016 | 2.01 | 0.300 | 0.233 |

Assuming the same standard deviations, the calculations were repeated and these values are shown in Table 37:

Table 37: Confidence limits for sample size beyond 100

| Category | Mean | Standard deviation | Standard sample error | Value of T | Upper confidence limit | Lower confidence limit |
|---|---|---|---|---|---|---|
| Physical performance | 0.297 | 0.073 | 0.011 | 1.96 | 0.318 | 0.275 |
| Economic impact | 0.241 | 0.088 | 0.013 | 1.96 | 0.267 | 0.216 |
| Environmental impact | 0.195 | 0.110 | 0.016 | 1.96 | 0.227 | 0.162 |
| Social impact | 0.267 | 0.111 | 0.016 | 1.96 | 0.300 | 0.234 |

As demonstrated, the values obtained for a sample size of 45 was fairly similar to those of a sample size of beyond 100. This is due mainly to the low standard deviations calculated from the samples, proving the results from such a small sample are reliable. Therefore, the results of the weight survey were carried forward to be used for the assessment methodology.

After careful examination of the obtained weights, the values showed that the weights for each of the four categories were fairly close. Physical performance scored slightly higher, and environmental impact scored slightly lower. This is the result of the careful selection of the number of participants as discussed earlier, which has succeeded in eliminating bias. The resulting weights are as detailed in Table 38:

Table 38: Weight survey results

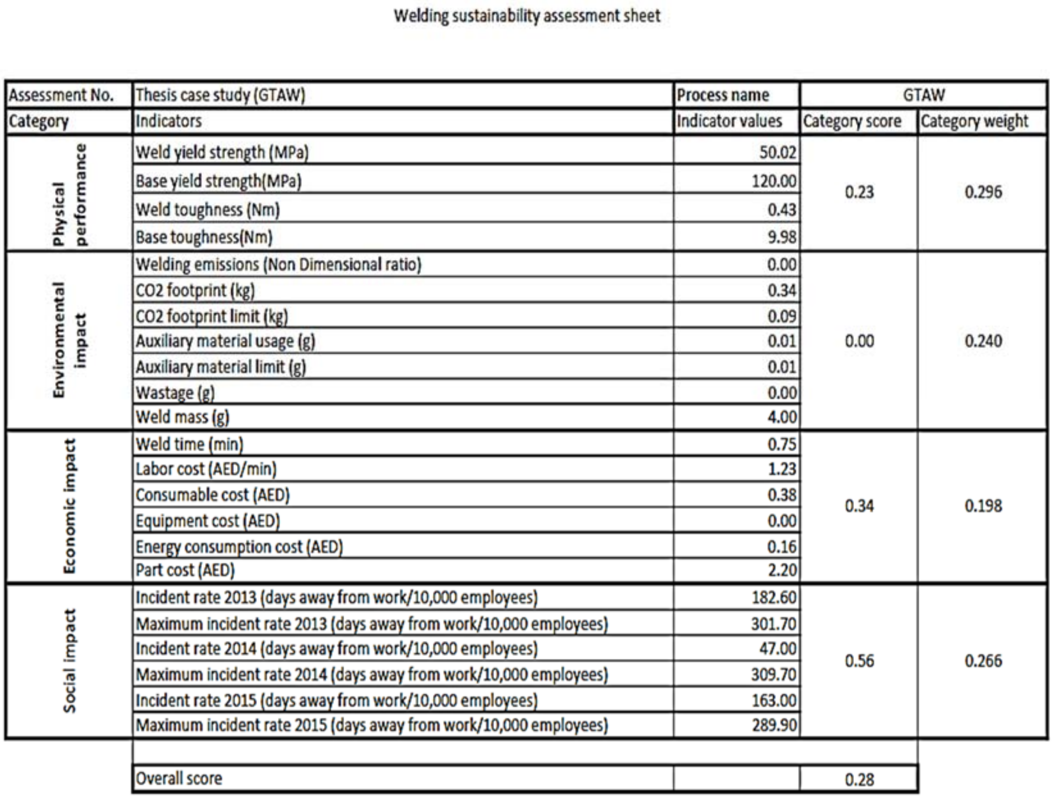
| Category | Survey weight |
|---|---|
| Physical performance | 0.296 |
| Environmental impact | 0.198 |
| Economic impact | 0.240 |
| Social impact | 0.266 |

In the next section, these weights were used to calculate the sustainability assessment scores by applying them to their respective categories.

## 3.6. Sustainability Scores

**3.6.1. GTAW.** Figures 46 and 47 shows the score of GTAW as 0.28, which is considered to be low. The reasons for having such a low score lie with the 0 score for one of the categories, namely the environmental impact. In terms of the environmental impact, it is the great energy input required for this process which had the biggest effect. This great energy consumption led to a carbon footprint greater than the allowable limit. This also drove the cost of the process to the expensive side. These contributions rendered this process the lowest performer amongst the other competitors.

Even if GTAW has performed fairly well in the physical performance category, this does not make it the best candidate for aluminum welding, given the current case study. Another usage for GTAW is to weld exotic metals, such as Inconel, Monel, and titanium, as the high temperature needed for the fusion of these materials can be achieved. A different study on these materials could yet result in GTAW's favor.



Welding sustainability assessment sheet

| Assessment No. | Thesis case study (GTAW) | Process name | GTAW | |
|---|---|---|---|---|
| Category | Indicators | Indicator values | Category score | Category weight |
| Physical performance | Weld yield strength (MPa) | 50.02 | 0.23 | 0.296 |
| | Base yield strength(MPa) | 120.00 | | |
| | Weld toughness (Nm) | 0.43 | | |
| | Base toughness(Nm) | 9.98 | | |
| Environmental impact | Welding emissions (Non Dimensional ratio) | 0.00 | 0.00 | 0.240 |
| | CO2 footprint (kg) | 0.34 | | |
| | CO2 footprint limit (kg) | 0.09 | | |
| | Auxiliary material usage (g) | 0.01 | | |
| | Auxiliary material limit (g) | 0.01 | | |
| | Wastage (g) | 0.00 | | |
| | Weld mass (g) | 4.00 | | |
| Economic impact | Weld time (min) | 0.75 | 0.34 | 0.198 |
| | Labor cost (AED/min) | 1.23 | | |
| | Consumable cost (AED) | 0.38 | | |
| | Equipment cost (AED) | 0.00 | | |
| | Energy consumption cost (AED) | 0.16 | | |
| | Part cost (AED) | 2.20 | | |
| Social impact | Incident rate 2013 (days away from work/10,000 employees) | 182.60 | 0.56 | 0.266 |
| | Maximum incident rate 2013 (days away from work/10,000 employees) | 301.70 | | |
| | Incident rate 2014 (days away from work/10,000 employees) | 47.00 | | |
| | Maximum incident rate 2014 (days away from work/10,000 employees) | 309.70 | | |
| | Incident rate 2015 (days away from work/10,000 employees) | 163.00 | | |
| | Maximum incident rate 2015 (days away from work/10,000 employees) | 289.90 | | |
| | | | | |
| | Overall score | | 0.28 | |

Figure 46: GTAW sustinability scores

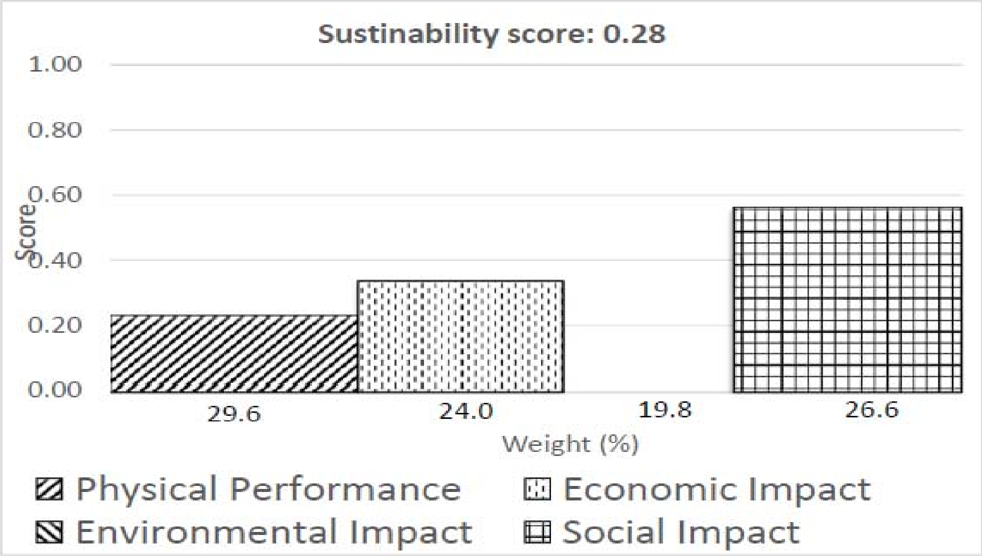
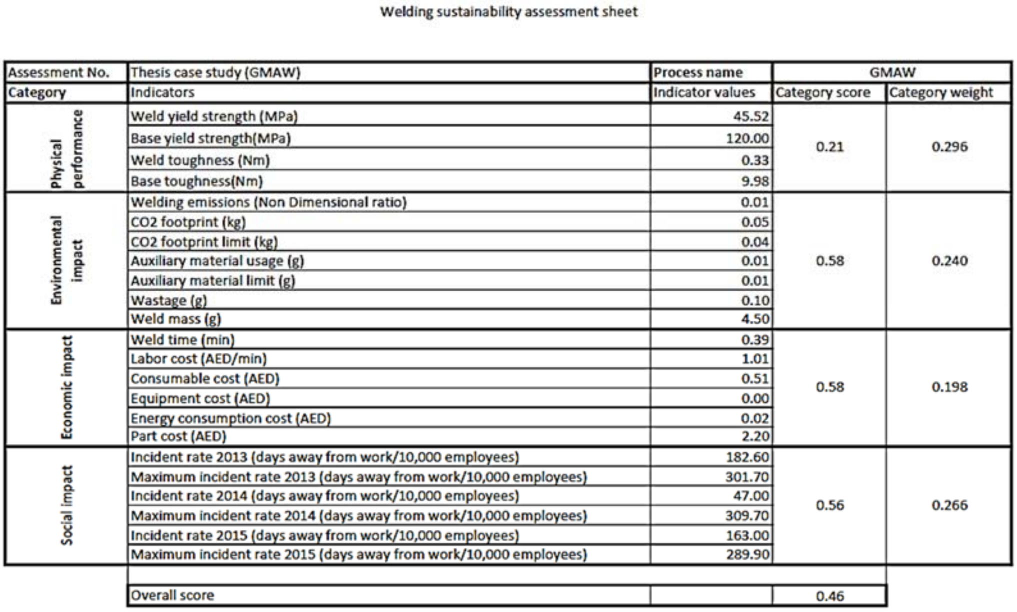


Figure 47: GTAW sustinability scores

**3.6.2. GMAW.** GMAW has scored higher than GTAW with 0.46. In spite of that, the score could also be deemed as low. As with GTAW, the social impact category score is again low, due to the bad incident rates. These incident rates have really affected the sustainability score of the arc welding process to the point where they can nearly be deemed as unacceptable in the presence of an automated process in the same comparison.



Welding sustainability assessment sheet

| Assessment No. | Thesis case study (GMAW) | Process name | GMAW | |
|---|---|---|---|---|
| Category | Indicators | Indicator values | Category score | Category weight |
| Physical performance | Weld yield strength (MPa) | 45.52 | 0.21 | 0.296 |
| | Base yield strength(MPa) | 120.00 | | |
| | Weld toughness (Nm) | 0.33 | | |
| | Base toughness(Nm) | 9.98 | | |
| Environmental impact | Welding emissions (Non Dimensional ratio) | 0.01 | 0.58 | 0.240 |
| | CO2 footprint (kg) | 0.05 | | |
| | CO2 footprint limit (kg) | 0.04 | | |
| | Auxiliary material usage (g) | 0.01 | | |
| | Auxiliary material limit (g) | 0.01 | | |
| | Wastage (g) | 0.10 | | |
| | Weld mass (g) | 4.50 | | |
| Economic impact | Weld time (min) | 0.39 | 0.58 | 0.198 |
| | Labor cost (AED/min) | 1.01 | | |
| | Consumable cost (AED) | 0.51 | | |
| | Equipment cost (AED) | 0.00 | | |
| | Energy consumption cost (AED) | 0.02 | | |
| | Part cost (AED) | 2.20 | | |
| Social impact | Incident rate 2013 (days away from work/10,000 employees) | 182.60 | 0.56 | 0.266 |
| | Maximum incident rate 2013 (days away from work/10,000 employees) | 301.70 | | |
| | Incident rate 2014 (days away from work/10,000 employees) | 47.00 | | |
| | Maximum incident rate 2014 (days away from work/10,000 employees) | 309.70 | | |
| | Incident rate 2015 (days away from work/10,000 employees) | 163.00 | | |
| | Maximum incident rate 2015 (days away from work/10,000 employees) | 289.90 | | |
| | Overall score | | 0.46 | |

Figure 48: GMAW sustainability scores

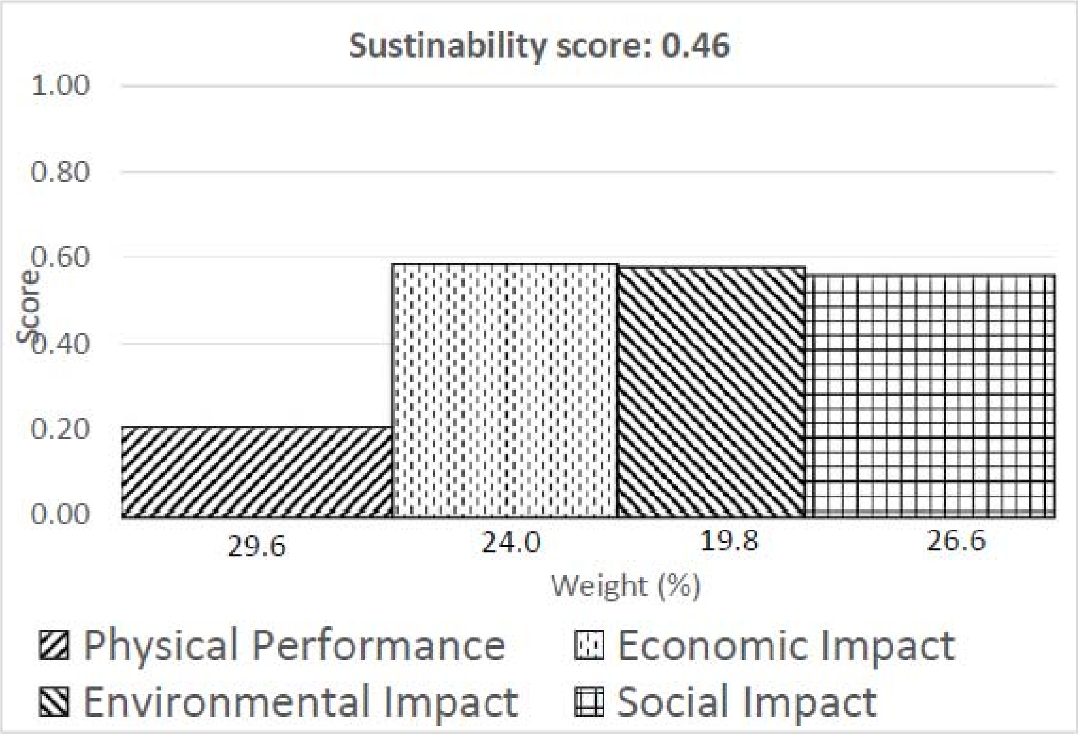
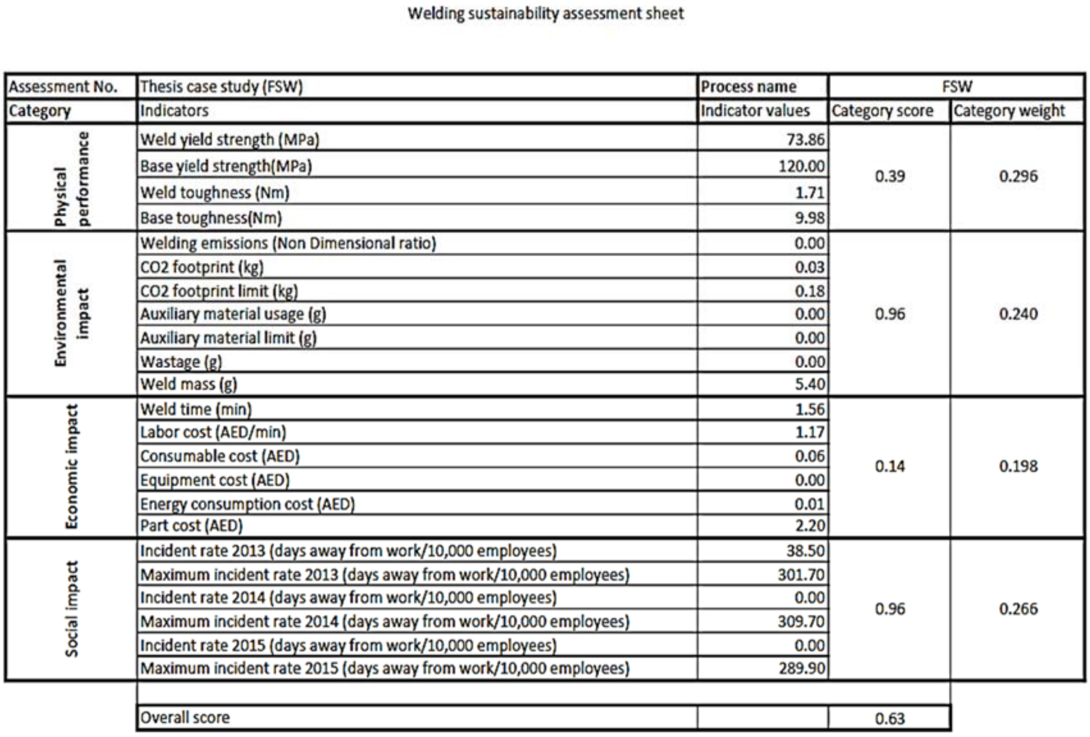


Figure 49: GMAW sustainability scores

It should be noted though that economically, GMAW is the highest performer between the three processes. It is the highest category score for this process, and should be noted as a distinct advantage between all the other processes. This ascertains why this process is being heavily deployed in various industries and applications.

Environmentally, the process scored a decent score, which is due to the relatively low energy consumption. This low consumption then reflected on to a low carbon footprint. Regardless, of the fact that it was the only process which produced emissions, the amount produced was very low. Therefore, the overall environmental impact score was good.

**3.6.3. FSW.** FSW scored the highest with an aggregate score of 0.63. The advantage of this process comes mainly from the contributions of the Social and the Environmental impacts. The scores from these categories were much higher for FSW than the other processes. In the case of the environmental impact, FSW does not consume a lot of energy and therefore the carbon footprint is low. Moreover, the process does not utilize any auxiliary material or produce emissions. In the social impact category, the fact that operating a machine is safer that welding by hand drops the incident rate to a very low value.



Welding sustainability assessment sheet

| Assessment No. | Thesis case study (FSW) | Process name | FSW | |
|---|---|---|---|---|
| Category | Indicators | Indicator values | Category score | Category weight |
| Physical performance | Weld yield strength (MPa) | 73.86 | 0.39 | 0.296 |
| | Base yield strength(MPa) | 120.00 | | |
| | Weld toughness (Nm) | 1.71 | | |
| | Base toughness(Nm) | 9.98 | | |
| Environmental impact | Welding emissions (Non Dimensional ratio) | 0.00 | 0.96 | 0.240 |
| | CO2 footprint (kg) | 0.03 | | |
| | CO2 footprint limit (kg) | 0.18 | | |
| | Auxiliary material usage (g) | 0.00 | | |
| | Auxiliary material limit (g) | 0.00 | | |
| | Wastage (g) | 0.00 | | |
| | Weld mass (g) | 5.40 | | |
| Economic impact | Weld time (min) | 1.56 | 0.14 | 0.198 |
| | Labor cost (AED/min) | 1.17 | | |
| | Consumable cost (AED) | 0.06 | | |
| | Equipment cost (AED) | 0.00 | | |
| | Energy consumption cost (AED) | 0.01 | | |
| | Part cost (AED) | 2.20 | | |
| Social impact | Incident rate 2013 (days away from work/10,000 employees) | 38.50 | 0.96 | 0.266 |
| | Maximum incident rate 2013 (days away from work/10,000 employees) | 301.70 | | |
| | Incident rate 2014 (days away from work/10,000 employees) | 0.00 | | |
| | Maximum incident rate 2014 (days away from work/10,000 employees) | 309.70 | | |
| | Incident rate 2015 (days away from work/10,000 employees) | 0.00 | | |
| | Maximum incident rate 2015 (days away from work/10,000 employees) | 289.90 | | |
| | | | | |
| | Overall score | | 0.63 | |

Figure 50: FSW sustainability scores

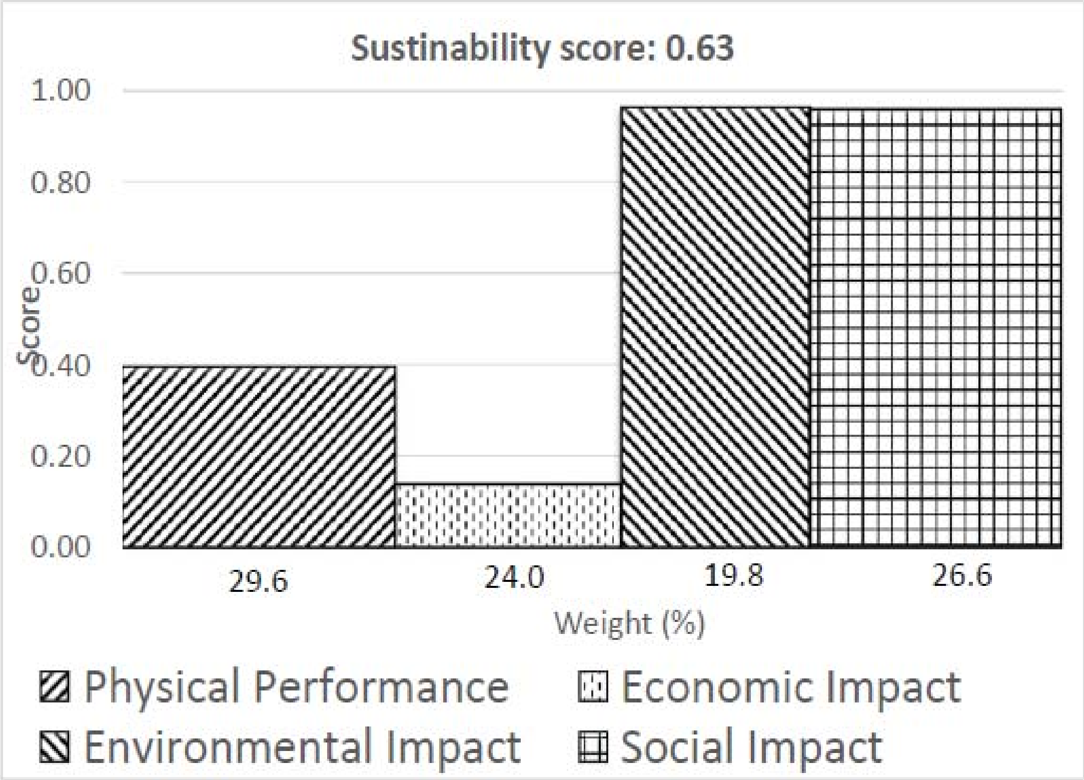


Figure 51: FSW sustainability scores

Even though the process does not seem very economical, with the lowest economic impact score, the advantages certainly outweigh the disadvantages.

In conclusion, Physical performance wise, GTAW was not the worst performer. It certainly fared better than the other arc welding process, GMAW, but it was not better than FSW. This is probably due to the specifics of this particular experiment. Aluminum as a base metal changes its physical properties significantly with a large heat input. This heat input is present in the two arc welding processes. However, FSW has been developed specifically to tackle this issue. The evidence for that is the fact that FSW performed better than the two arc welding processes.

In the economic impact category, it was GMAW that has performed exceptionally well. GTAW was acceptable as well, but the score of FSW was very low. This is because of the higher cost of the FSW tool when compared to the relatively cheap fillers used in the arc welding process. This difference in the cost comes from the opposing viewpoints when designing the particular filler material and the FSW tool. The arc welding fillers are designed in such a way that they are consumable, easy to transport, easy to store, and easy to use. On the other hand, the FSW tools are designed with a long life and accuracy as an objective. Additionally, these tools are not meant to be simple tool, but as means to perform technologically new methods of welding which require a good amount of expertise before operation. This leads to having the 2 approaches having very different costs. It is up to the other category scores to justify the investment of FSW.

The environmental impact category was unquestionably dominated by FSW. It should come as no surprise that a process that does not produce any emissions, does not use auxiliary material, and has a reasonable carbon footprint scores in this category. This places FSW at a definite advantage against the other processes. GMAW had a fairly good performance, but GTAW, due to a massive carbon footprint, scored a 0. It appears that these are simply traits of the processes themselves, and a trend similar to the one seen in this study would appear in other similar studies.

Analyzing the social impact category was fairly direct. Simply speaking, the incident rate of arc welding processes has been found to be very high compared to FSW. This led to the category score for the arc welding process to be reasonably lower than FSW. This is because the high incident rate is an indicator that the arc welding processes are main contributors to the high overall incident rate. It appears that the industry can still use some research in improving safety for arc welding processes.

Ultimately, after analyzing the aggregate and category scores, it can be concluded that for this particular welding application, FSW is the most sustainable process. It had the highest physical performance, social impact and environmental impact score. It may have scored the least on the economic impact, but the lower weightage on that category undermined the score, and the scores of the other categories helped push the overall score upwards.

# Chapter 4. Summary and Future Work

## 4.1. Summary

With the recent economy crises, the world has turned to cost cutting, downsizing, and mass layoffs as measures by which to mitigate the situation and make up some of the losses. However, this has not guaranteed a constant level of performance and quality. In addition to that, the crises gave already reluctant individuals a bigger excuse to avoid including plans for the reduction of environmental damage in their plans for development. This could have a devastating effect on the global environment. This is why a new concept is required to give a better, holistic approach to the assessment of products, companies, processes, etc.

Sustainability is a concept which guarantees that the products, processes, and companies operate properly within environmental limits, maximizing profits, and guaranteeing society’s satisfaction. It gives a more holistic approach to development and assessment. This is why sustainability has been receiving a lot of attention and support lately. This thesis has provided a general sustainability assessment methodology, which was then adapted to provide a tool to specifically assess the sustainability performance of welding processes.

This was done through choosing four categories for assessment, namely physical performance, economic impact, environmental impact and social impact. Relevant indicators, specific to the application of welding, were selected for each category based on a thorough literature review on sustainability and studies performed on welding. Each of these categories was scored using an equation developed from the category specific indicators. To combine these scores in to a single sustainability score, a weighted average method was suggested. A survey would be carried out to ask experts to give the weights of each category.

This methodology was tested on a case study to compare three different welding processes: GTAW, GMAW, and FSW. The processes were studied for the welding of Aluminum alloy 5083 plates. The results of the case study showed that GTAW was the worst performer because of two main reasons. First, the process consumed a lot of energy and this affected the economic impact score severely. The other reason was concerned with the very high incident rates for arc welding. This also caused the social impact score to plummet. It should be noted that the social impact score effect was the same for GMAW as well. GMAW ranked second in the study. In spite of the low social impact score, the process gained leverage from the outstanding economic impact category score. This is mainly credited to how low the running cost for this process is. Ultimately, though, it was FSW that had the highest score among the three processes. It has outdone the other process in two main areas in particular; physical performance and social impact. In spite of FSW being the most expensive process in this study, and scoring the lowest in the economic category, the positives have definitely outweighed the negatives. Therefore, it can be concluded that the technology and investment of FSW are worth the effort, money and time as FSW is the most sustainable process.

## 4.2. Future Work

To develop and enhance the idea of sustainability in general, the suggested methodology should be adapted to other applications. The methodology suggested in this thesis is relatively flexible. A change to the indicators would probably be easily adapted to other applications. This would help determine the general effectiveness of the suggested methodology. If found lacking in some area, a suitable modification may be applied.

A more specific study that may be carried out using this methodology would be another case study with different welding processes, or different materials welding. Performing a new case study should mean that the suggested methodology may be used as suggested in this thesis. However, depending on the end user on the user’s own objective, the methodology may need minor adjustments. This can be especially applied to the physical performance category in the suggested methodology.

Finally, this methodology could be standardized. By doing that, processes would not have to be assessed against each other. Rather, any welding process could be assessed for a particular welding application against a scale. This standardized score could be used for cost control tracking and plans for improvement. However, in order for that to happen, a specific regional/global standard for welding must be established. Once that scale is accepted, the methodology can be used to score a welding process over successive years to observe and measure the change in performance.

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# Vita

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