ENVIRONMENTAL IMPACT ANALYSIS OF OIL AND GAS PIPE REPAIR TECHNIQUES USING LIFE CYCLE ASSESSMENT (LCA)

BY

FARHAN ASHRAF

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DEANSHIP OF GRADUATE STUDIES

This thesis, written by **FARHAN ASHRAF** under the direction his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN MECHANICAL ENGINEERING.**

Dr. Mian Mobeen Shaukat
(Advisor)

Dr. Zuhair M. Asad Gasem
Department Chairman

Dr. Mohammad Asif
(Member)

Dr. Salam A. Zummo
Dean of Graduate Studies

DEANSHIP OF GRADUATE STUDIES

Dr. Sulaiman Pashah
(Member)

9/6/16
Date

Dedicated to my Mother, my Father, my Siblings, my Nieces and my Teachers

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LIST OF ABBREVIATIONS

LCA	Life Cycle Assessment
SETAC	Society of Environmental Toxicology and Chemistry
REPA	Recourses and Environmental Profile Analysis
ASME	American Society of Mechanical Engineers
MRI	Midwest Research Institute
SEAC	Safety and Environmental Assurance Center
TRACI	Tool for Reduction and Assessment of Chemical Impacts
ISO	International Organization of Standardization
EPA	Environmental Protection Agency
FU	Functional Unit
LCIA	Life Cycle Impact Assessment
USLCI	United States Life Cycle Inventory
ELCD	European Reference Life Cycle Database
EPS	Environmental Protection Strategy
ODP	Ozone Depletion Potential
GWP	Global Warming Potential
HTP	Human Toxicity Potential

AP	Acidification Potential
EP	Eutrophication Potential
ADP	Abiotic Depletion Potential

ABSTRACT (ENGLISH)

NAME: **FARHAN ASHRAF**

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Pipe repair is an important process in oil and gas industry. It is carried out to avoid replacement of a pipe and to stop propagation of pipe damage. Several repair techniques are currently used in the industry. These techniques include weld patch, weld buildup, mechanical clamp, composite wrap, flush welded patch, non-metallic internal lining of pipe etc. This thesis investigates the environmental impact of four pipe repair techniques: Fillet welded patch, weld buildup, mechanical clamp, and non-metallic composite overwrap currently used in Saudi Arabian oil and gas industry. Life Cycle Assessment (LCA) methodology was used to determine the most environment friendly repair solution. Using industry standards and guidelines from industry experts, four repair processes were conducted in the lab and data was collected for energy and material consumption. Next LCA was performed using SimaPro software. Following impact categories were used to gain the understanding of environmental impact of these repair techniques: abiotic depletion, abiotic depletion (fossil fuel), global warming potential, ozone depletion potential, human toxicity, fresh water aquatic ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification potential and eutrophication potential. The results of the study show that for 10 year’s repair life, non-metallic composite overwrap has significantly higher global warming potential, acidification potential, photochemical oxidation potential, and eutrophication potential. Furthermore, mechanical clamp has highest human toxicity potential and terrestrial ecotoxicity potential. Fillet welded patch has the least environmental impact among the above mentioned processes. In case of non-metallic composite overwrap, the environmental impact is mostly influenced by transportation and material usage. Sensitivity analysis was conducted to suggest ways to reduce the environmental impact of these repair processes.

ملخص الرسالة

الاسم: فرحان أشرف

العنوان: دراسة تحليلية للتأثير البيئي لطرق إصلاح أنابيب الغاز والزيت باستخدام حساب دورة الحياة (LCA)

التخصص: الهندسة الميكانيكية

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تعد عملية إصلاح خطوط الأنابيب من العمليات المهمة في صناعة الزيت والغاز. تستخدم هذه العمليات تجنباً لاستبدال الأنبوب بالكامل ولإيقاف تمدد الشروخ فيه. حالياً يوجد في السوق العديد من تقنيات الإصلاح. هذه التقنيات تتضمن fillet weld patch، weld buildup، mechanical clamp، composite wrap، flush welded patch, non-metallic internal lining of pipe , والخ. هذه الرسالة العلمية تبحث في التأثير البيئي لأربع عمليات إصلاح مختلفة وهي fillet weld patch، weld buildup، mechanical clamp , and non-metallic composite overwrap مستخدمة حالياً في سوق الزيت والغاز السعودي. اعتمدت هذه الدراسة على مبدأ حساب دورة الحياة في تحديد أفضل الطرق تأثيراً على البيئة. وفقاً للمعايير المعتمدة وإرشادات خبراء الصناعة تمت علمية اختبار طرق الإصلاح الأربع في المعمل وتم تسجيل بيانات المواد المستخدمة وكميات الطاقة المستخدمة في كل طريقة من طرق المعالجة. بعد ذلك تم تنفيذ عمليات محاكاة حساب دورة الحياة باستخدام سوفتوير (SimaPro). من أجل فهم أفضل للتأثير البيئي اعتمدت الدراسة على تقسيم العوامل المؤثرة إلى فئات تأثير مختلفة وفقاً لاحتمالية المساهمة في التأثير الحراري، المشاركة في عمليات الأكسدة، توليد الأوزون الضوئي-كيميائي، استنزاف الموارد الغير حية، تسمم الإنسان، تسميم النظام البيئي في المياه العذبة، تسميم البيئة البحرية، استنزاف طبقة الأوزون، تسميم

المناطق البرية. باستخدام فترة العشر سنوات كعمر افتراضي لعمليات الإصلاح فقد توصلت الدراسة إلى أن non-metallic composite overwrap لها تأثير سلبي بيئي كبير فيما يتعلق بالتأثير الحراري, المشاركة في عمليات الأكسدة, توليد الأوزون الضوئي-كيميائي. إضافة إلى ذلك فإن عمليات ال mechanical clamp ذات تأثير كبير من ناحية إحتمالية تسمم الإنسان والبيئة الأرضية. على العكس من ذلك فإن علميات ال fillet weld patch هي أفضل العمليات الأربع من ناحية التأثير البيئي بشكل إجمالي. الجدير بالذكر أن كمية المواد المستخدمة وعمليات النقل قد لعبت الدور الأكبر في التأثير البيئي لعمليات ال non-metallic composite overwrap. أخيراً فقد تم إجراء دراسة تحليلية من أجل اقتراح طرق لتقليص التأثير البيئي السلبي لكل من طرق الإصلاح الأربع.

CHAPTER 1

INTRODUCTION

Sustainability has become an important issue in recent years for global industries. Researchers have realized that modern industrial processes have serious impacts on environment. Climate change due to continuously increasing global warming potential and adverse impacts on human ecosystem are the important environmental issues. Therefore, it becomes imperative to measure and analyze the implications of industrial processes on the environment.

Oil and gas sector is one of the largest industrial sector in the world which has seen rapid growth and transformation in the recent history. Oil and gas sector is potentially one of the high risk sectors to both human beings and natural environment [1]. From environmental perspective, emissions from oil and gas sector are considered most hazardous as it ranges from exploration to distribution process. The environmental impacts which are highly affected by this sector are global warming potential, acidification potential, fresh water aquatic ecotoxicity and terrestrial ecotoxicity [1]. Environmental impacts due to oil and gas leakage have already been reported in literature [1]. However, some processes like pipeline repair are still needed to be investigated with the aim of sustainable development and environmental protection.

In oil and gas sector, Saudi Arabia has the world's largest reserves of petroleum liquid and it is the second largest producer of crude oil after Russia [2]. Moreover, Saudi Arabia is the Middle East's fastest growing consumer of energy because of its rapidly growing population and large scale development projects [2]. Saudi Arabia has huge oil and gas sector, in which there is constant demand for experienced companies and quality products in the fields of engineering, design, construction, consulting and oil transportation.

Pipelines are most economical and efficient way to transport oil and gas [3]. Saudi Arabia has a large network of pipelines across the region for transportation of oil and gas. Due to erosion and corrosion, these pipelines deteriorate over time. Therefore, regular pipeline maintenance is required for successful operation. Pipeline maintenance involves either replacement of pipes or repair of damaged/corroded regions on pipes. Depending upon the type and nature of a defect, several different repair methods are used. Common repair methods used in oil and gas industry are fillet welded patch, flush welded patch, weld buildup, mechanical clamp, non-metallic composite repair system and non-metallic lining of pipe etc. These repair techniques employed in oil and gas industry need to be investigated from perspective of sustainable development.

Life Cycle Assessment (LCA) is an important methodology to support environment friendly product design and can be used to investigate and compare environmental impacts of industrial processes. LCA is a method of collecting information and translating it into useful form so that decision makers can make informed environment friendly decisions. An overview of most important aspects of LCA and general procedure of conducting LCA is described below.

1.1 Life Cycle Assessment (LCA)

LCA is a technique to investigate environmental impacts of a product or a process. LCA examine all stages related to a product or a process as shown in Figure 1. Major stages are characterized by International Organization of standardization (ISO) and include extraction of natural resources, production, manufacturing, distribution, utilization, recycling and disposal [4]. Figure 1 depicts a general framework for LCA.

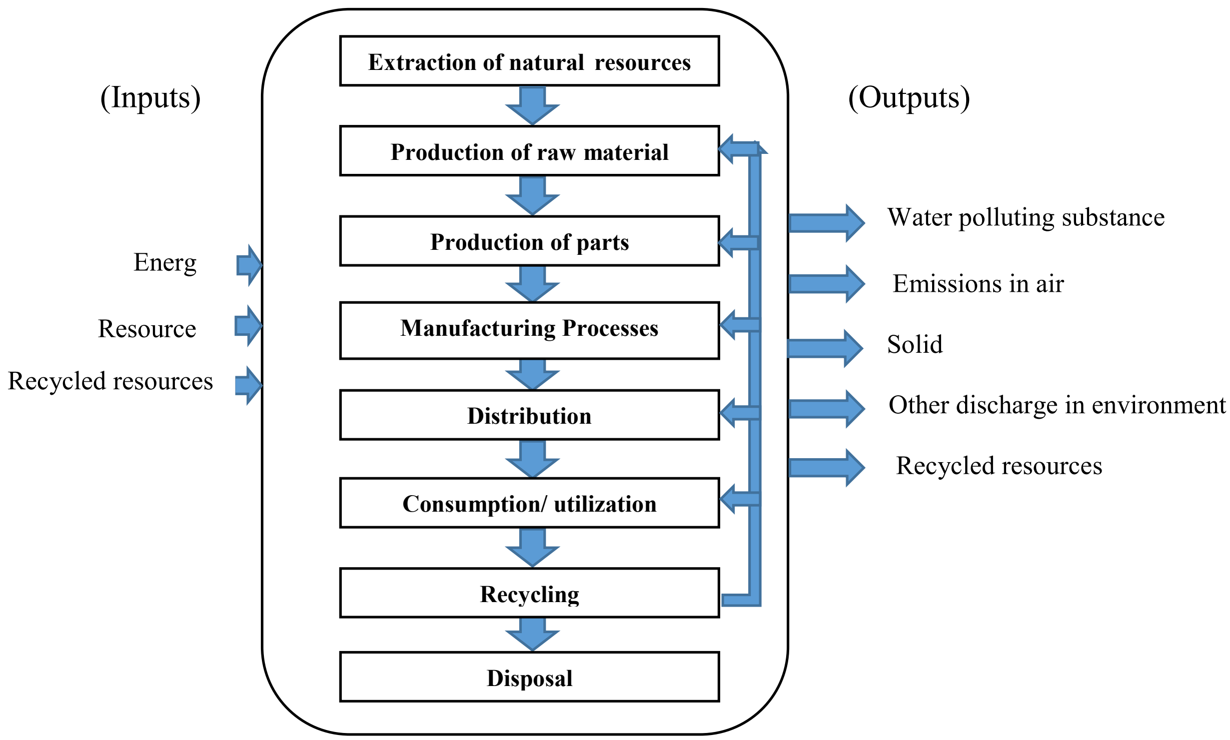

Figure 1: General Framework of LCA

LCA considers energy and resources needed at each stage of life cycle along with emissions and wastes produced (Figure 1). LCA can be conducted to identify environmental emissions at various stages of a product, to benchmark various products, to guide policy making, and for supporting environmental labeling of products.

1.2 Brief History of LCA

In this section, brief history of LCA will be elaborated. The development of LCA can be categorized into three periods i.e. 1970-1990, 1990-2000 and 2000 onwards. The first period (1970-1990) was called the decade of conception in which resource and energy efficiency, waste issues and pollution control were the primary concerns. One of first studies was conducted in 1969 about the emissions of Coca Cola beverages containers by Midwest Research Institute (MRI) [5]. In the recent past, the same institute conducted a study for U.S Environmental Protection Agency. At that time, MRI used the term Recourses and Environmental Profile Analysis (REPA) for this study. After a declining period of public interest, in 1984, Swiss Federal Laboratories for Testing (EMPA) reported the summary of data required for LCA [5]. This period consisted of widely diverging approaches and terminologies. Most of LCAs studies were performed without a common framework.

The period 1990-2000 was significant for the growth of LCA. Society of Environmental Toxicology and Chemistry (SETAC) played a leading role and introduced the first "code of practice", a framework for LCA [5]. Several impact assessment methods were developed in this period such as endpoint and damage approaches [5]. Afterwards, the International Organization of Standardization (ISO) has been involved in LCA since 1994 [5] and accepted the task of standardization of method and wrote the standard ISO 14040.

In recent years, the demand of LCA has increased. ISO modified some of the steps in LCA framework presented by SETAC in 2006 which is being practiced as ISO 14040 globally. The current LCA mainly focuses on the environmental aspects of sustainability. However, the other dimensions pertaining to sustainability like social and economic are still not incorporated in LCA [5]. Some applications of LCA in industry are discussed in the next section.

1.3 LCA Applications

Many companies are using LCA for designing new products as well as comparing new and existing products. Unilever, a leading Dutch consumer goods company, has been using LCA for their product innovation, product category analysis and strategic innovation [5]. Unilever performed LCAs of 1600 products. The results represent that factories contribute 3%, raw material suppliers share 26%, and consumers add up to 68% of overall carbon footprints [5]. Another study related to tea bags was conducted by Unilever. They analyzed that in order to connect tea bag and carton handle, zinc plated iron staples were used. This iron staple found to have large contribution in environmental impact of tea bag. The staple was then replaced by sewing connection.

Philips established a sustainable lighting solution with the help of LCA. Their bulbs contain less mercury, are energy efficient and last longer which reduce lamps in landfill and overall have low impact on environment. Procter and Gamble used LCA to make their supply chain management sustainable. They launched sustainable supply chain management program to link social responsibility and environmental sustainability with business operations and values [5].

Similarly, Husqvarna AB, the largest outdoor power product production company is also actively working to make their products and processes environmental friendly. The company used LCA to analyze the environmental impact of their lawnmowers. They found that production phase contribute dominant impact and environmental performance of lawnmower can be improved by increasing the recycling of metals [6].

Dyson, a home and office appliance manufacturer, published a report comparing the environmental impact of their products with other available options. Study concluded that aluminum Dyson hand dryer has low environmental impact as compared to other standard hand dryers. Study also revealed that using paper towels for drying hands is less environment friendly as compared to Dyson hand dryer [7].

Similarly, many other companies are using life cycle assessment for calculating the environmental impacts of their products and for decision making purposes. The framework of LCA which is being followed presently is according to ISO 14040 and is explained in the following section.

Steps in LCA

The procedure for conducting the LCA is defined by ISO and it is depicted in Figure 2. It consists of four steps namely: Goal and scope definition, inventory analysis, impact assessment and interpretation.

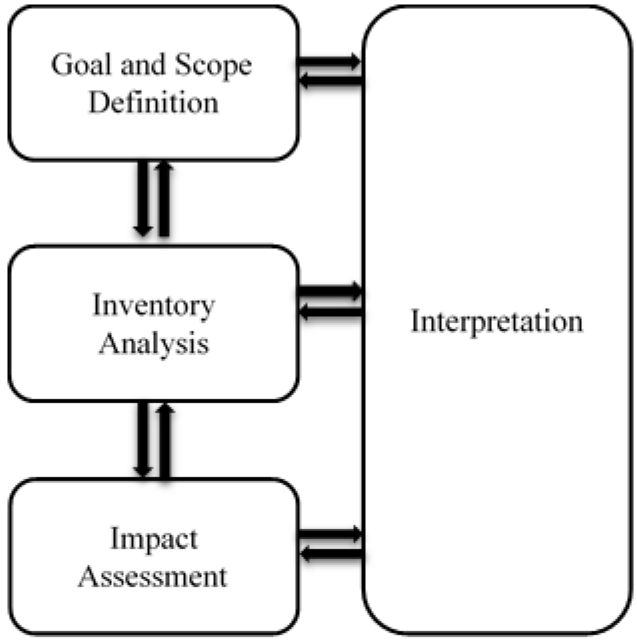

Figure 2: Steps to Conduct LCA

Goal and Scope Definition

The first step of analysis is to define the purpose of study [5]. The researcher might want to know which part of the study has lower environmental impact than its counterpart, or how the design can be improved or process can be changed to lower its environmental impact. One should be clear about the following preliminary things before starting the analysis [4].

- Purpose of the study
- Intended application of study
- Method, assumption and impact limitations
- Target audience

According to ISO 14040 [4], the scope of LCA includes the following.

1. Function: The useful service provides by the process
2. Functional unit: It quantify the identified function and it should be measureable
3. Reference flows: Amount of product required to fulfill the function
4. Data categories: Primary or secondary data

Function in LCA is defined as the useful service provide by a product or a process. Functional unit quantify the function and reference flow is the amount of product required to fulfill function. If two or more things are being compared, their functional units must be the same [8]. Functional unit (FU) allows us to compare two different products or processes. For example, two grocery bags: Plastic and paper can be compared. A reasonable functional unit will be the volume of groceries that can be carried by each bag. One plastic grocery bag cannot be compared with one paper bag because most paper grocery bags are larger in size as compared to plastic grocery bags. However, we can compare one plastic bag to 2/3 of a paper bag if it contains the same volume of groceries.

System boundaries must be defined in scope phase of study in terms of life cycle stages. LCA have different types of analysis based on life cycle stages e.g. cradle to grave, cradle to gate and cradle to cradle. If the study included all the life cycle stages from extraction of raw material to final disposal as shown in Figure 1, this is called cradle to grave LCA analysis. If study considered only the extraction of material and production stage, then this type of analysis is called cradle to gate LCA analysis. If a product is recycled into new product at the end of its life, so this type of analysis is called cradle to cradle analysis because there is no waste [5].

Inventory Analysis

Life cycle of products involves thousands of individual flows. Flows are defined as the inputs and outputs of the processes involved in the life cycle of a product or a process. However, depending upon the goal and scope of the analysis and time for conducting the research, all flows cannot be considered. Therefore boundaries must be defined [4]. For example, in any life cycle study, if a truck is used as a mean of transportation, the environmental impacts associated with truck manufacturing may not be considered.

The most important step in LCA is inventory analysis that encompasses collection and modeling of relevant data. Data is comprised from individual inflows and outflows [8], as shown in Figure 3.

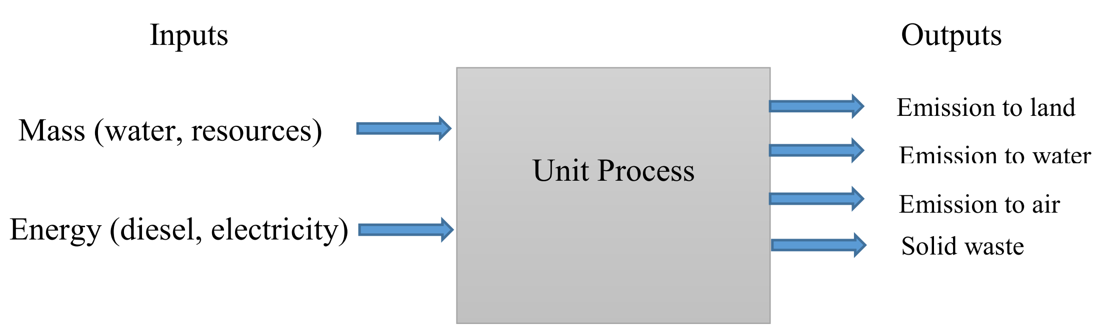

Figure 3: Inflows and Outflows in a Unit Process

The flows are scaled to the model's functional unit for every process. Some primary sources used to collect the data for the LCA inventory are as follows.

- Process measurement over the time
- Utility bills
- Process monitoring softwares

- Meter reading from the equipment
- Company data logs and records

At the end of inventory analysis, researcher have the data representing amount of resources and energy consumed, emission etc. throughout the life cycle [8]. Several software packages and databases have been developed to conduct LCA. Two most commonly used software packages are SimaPro and Gabi [5]. These packages allow user to create an inventory by selecting the right processes present in the database of software. Ecoinvent is one of the most popular European database used in these software. As LCA is extremely popular in Europe so most of the data in these software packages is based on European information. Therefore, if local values are available, user should substitute those values in place of European values [9]. Otherwise European values are used to calculate the environmental impact.

Impact Assessment

Life cycle impact assessment is a phase in which magnitude of potential environmental impacts are evaluated [5]. ISO 14040 [4] outlines the general method for performing impact assessment. The steps in a formal impact assessment include

- Selection of desired impact category.
- Classification of inventory results in the appropriate impact category.
- Characterization of impact in each category.
- Optional analysis such as weighting of impacts in different categories, so they can be compared.

Impact assessment is basically a characterization step which involves transformation of LCI results into common units and then results are combined within same impact category. Impact category is the central element of impact assessment method. ISO 14044 defines impact category as “class representing the environmental issues of concern to which life cycle inventory result may be assigned.”

The impact categories are chosen based on impact assessment methods such as TRACI, CML, ReCiPe, ILCD and IMPACT 2002 [5]. These methods either are based on midpoint approach or end approach. Midpoint approach or problem oriented approach, translates the impacts into environmental themes such as climate change, acidification and human toxicity etc. [5]. Whereas, endpoint approach or damage oriented approach translates the environmental impacts into issues of concern such as natural environment, natural resources and human health [5]. The brief account of aforementioned methods have been cited in the following section.

TRACI 2.1 is used as an impact assessment method. This method is developed by the U.S. Environmental Protection Agency (EPA) with the inputs consistent with U.S. locations [10]. In the case when location is undetermined, U.S. average values that exists in database, are used [11]. TRACI 2.1 is midpoint oriented life cycle impact assessment method including the impact categories acidification, global warming potential, ecotoxicity, eutrophication, ozone depletion, human health, land use and fossil fuel depletion [12].

CML is an impact assessment tool is named after the research institute (Center of Environmental Science of Leiden University) and developed by a group of researchers working at center of environmental science of Leiden University. It was presented as a midpoint approach methodology to analyze the environmental impact in 2002 [13]. The

CML method was based on the problem-oriented approach and includes impact categories: Abiotic depletion, abiotic depletion (fossil fuel), global warming potential, ozone depletion potential, human toxicity, fresh water aquatic ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification potential and eutrophication potential.

Eco Indicator 99 is a damage oriented impact assessment method in which resources extraction and emission are expressed in more than 10 impact categories. These impact categories was generalized to three impact categories by panel of Swiss LCA interest group [14] which are damage to human health, damage to ecosystem and damage to resources.

ReCiPe method is the modified form of CML and Eco-Indicator methods. The method was developed to incorporate the damage oriented approach of Eco indicator and problem oriented approach of CML and to reduce the uncertainty. The downside of this method is that it includes many impact categories which make results complex. Therefore most of midpoint categories are aggregated to give only three end point categories: Human health, ecosystem and resources [14].

Interpretation

The last step of LCA is interpretation of impact assessment results. The basic elements of the interpretation are as follows

- Identification of the hotspot (impact category having largest impact on environment) based on the inventory and impact assessment step.
- Check the validity of the results.
- Communicate conclusions, limitations and recommendations in appropriate way.

1.4 LCA Software

Establishing the life cycle inventory data for multiple unit processes and converting them into environmental impacts manually is a tedious and time consuming task. Also, it is almost not possible to collect all the data needed to model every underlying process in the manufacturing chain of product. Therefore, LCA heavily relies on software tools not only to model the unit processes data but also, to calculate the environmental impact of these processes [6].

SimaPro is one of the most popular LCA tools developed by Pre Consultants. SimaPro solves a product system by highly efficient algorithm which allows the computing of thousands of processes in a single calculation. The contribution of each step to final result is available after the calculation [6]. In SimaPro, many unit processes combine as an input to give one product which must be the output of process. SimaPro follows the ISO 14040 guidelines for conducting LCA. An overview of using SimaPro for conducting LCA is presented in the following section.

The main window after opening a project in SimaPro is shown in Figure 4, which basically shows the four steps of LCA according to ISO 14040 i.e. goal and scope, inventory, Impact Assessment and interpretation. The goal and scope section of SimaPro allows the user to enter the information about study. Also, it allows user to include or exclude the libraries. SimaPro has different built-in libraries such as Ecoinvent, USA input data etc. which contains the data of thousands of processes of different regions of world.

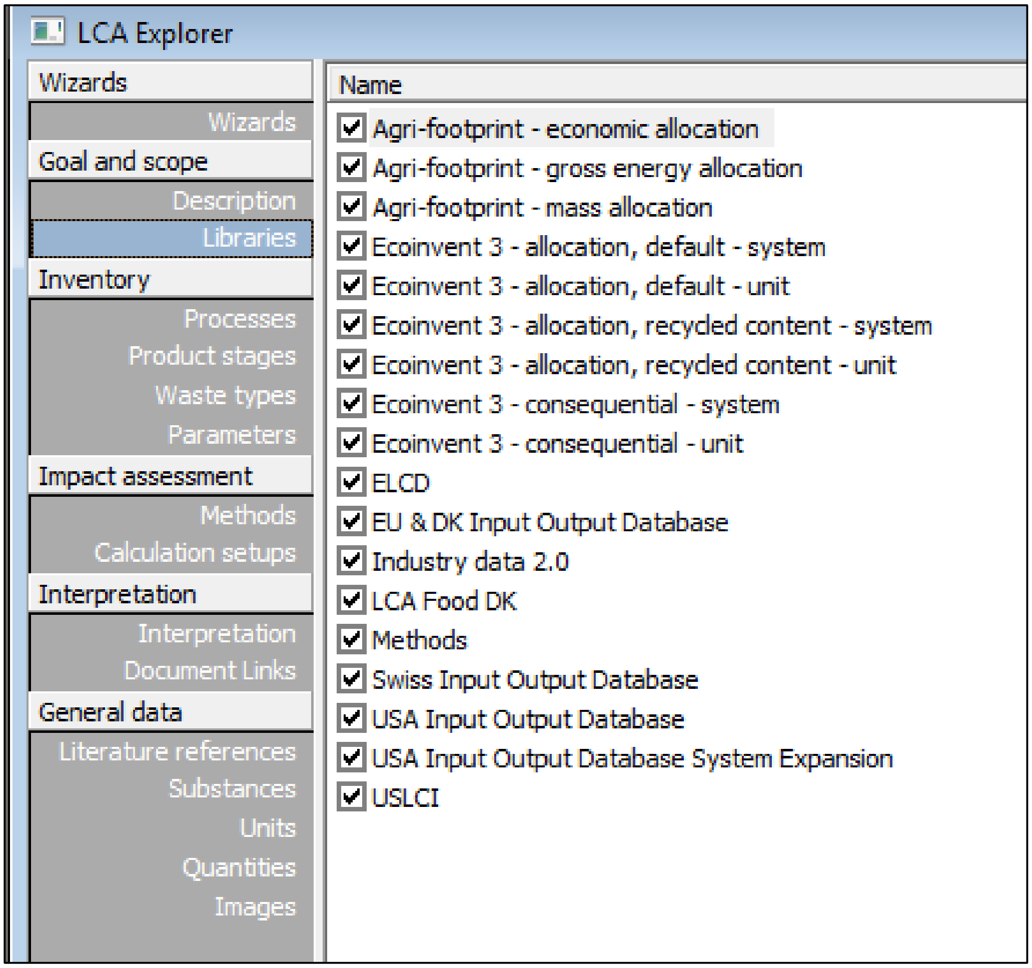

Figure 4: SimaPro Libraries

In inventory section, thousands of processes data related to different material and industry processes are available depending upon the libraries included in the project as shown in Figure 5. These processes are used in creating the assembly of product or a process in the next 'product stages' tab. Waste types are defined depending upon the goal and scope of study. The last step in inventory section allows the user to define parameter for sensitivity analysis.

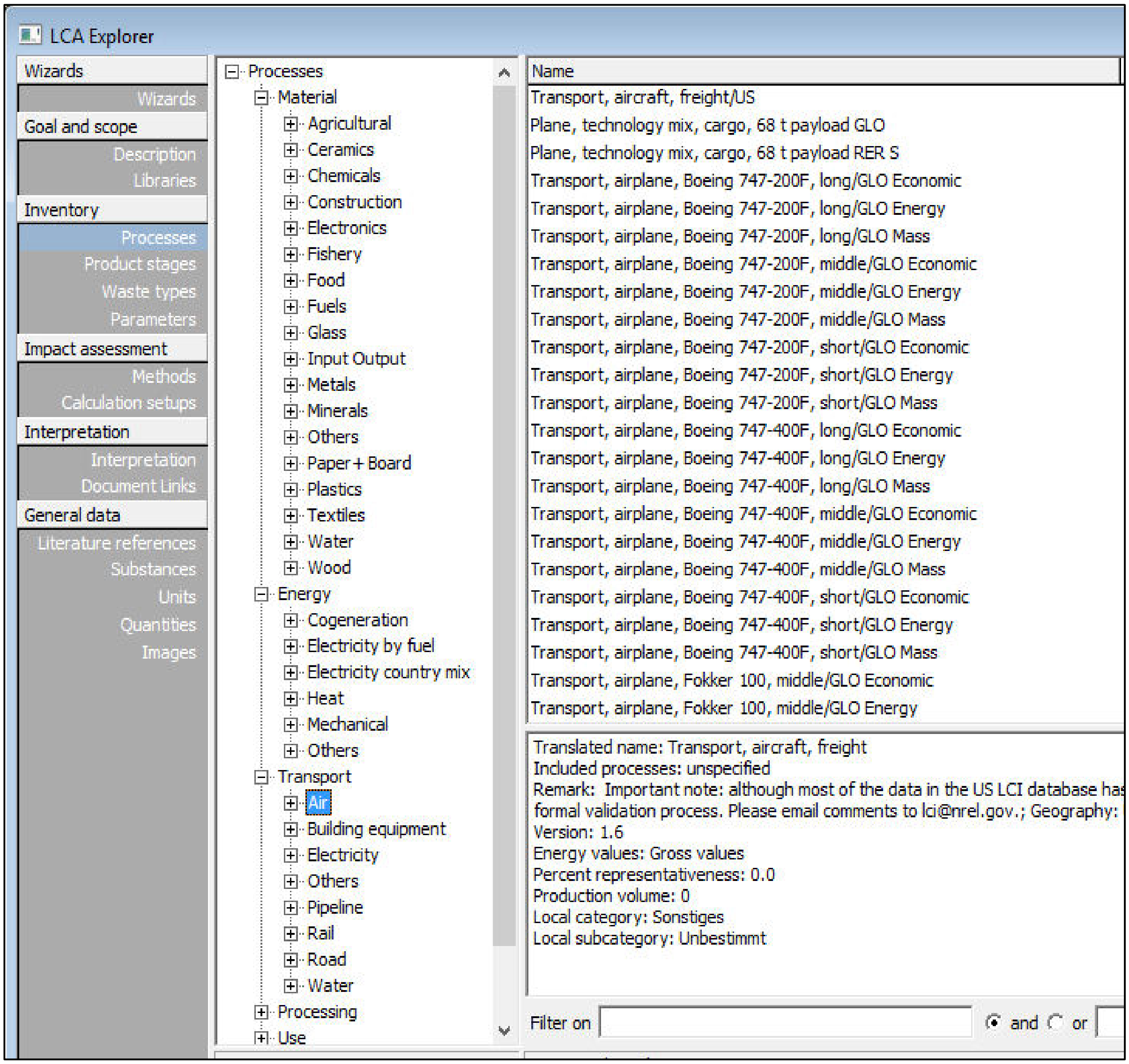

Figure 5: SimaPro Processes Data

Several life cycle assessment methods are available in SimaPro for calculating environmental impacts as shown in Figure 6. These impact assessment methods are based on regions normally in which LCA is being conducted. In calculation step, impact assessment is performed with the help of these methods. Life cycle impact assessment results and process tree are shown in Figure 7. Finally results are interpreted in last section of LCA.

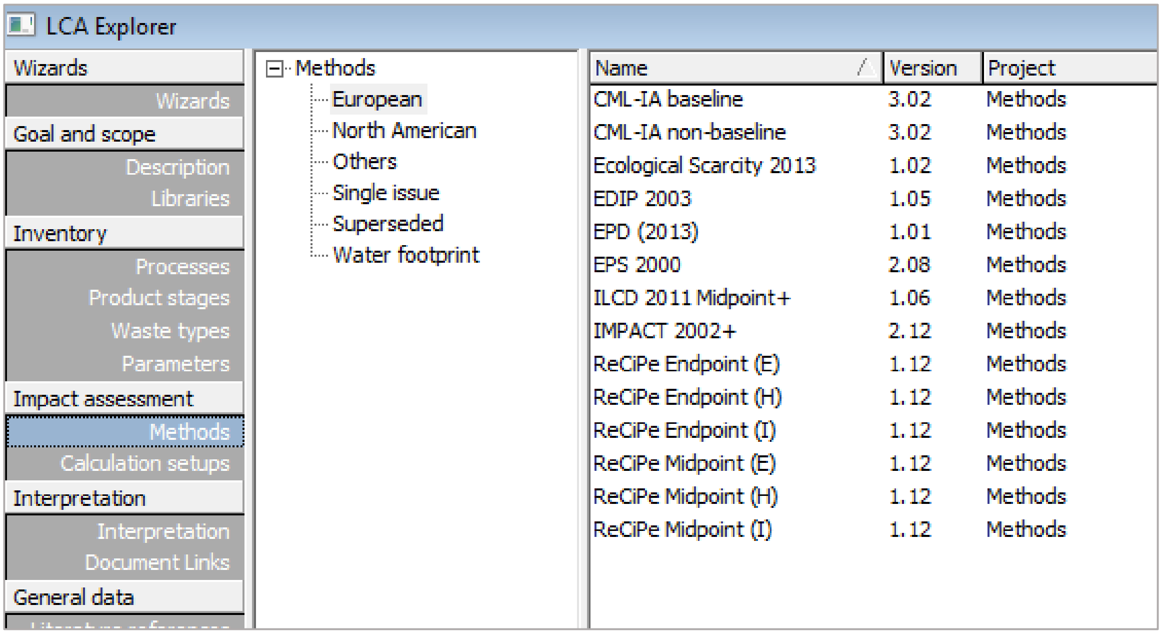

Figure 6: Impact Assessment Method in SimaPro

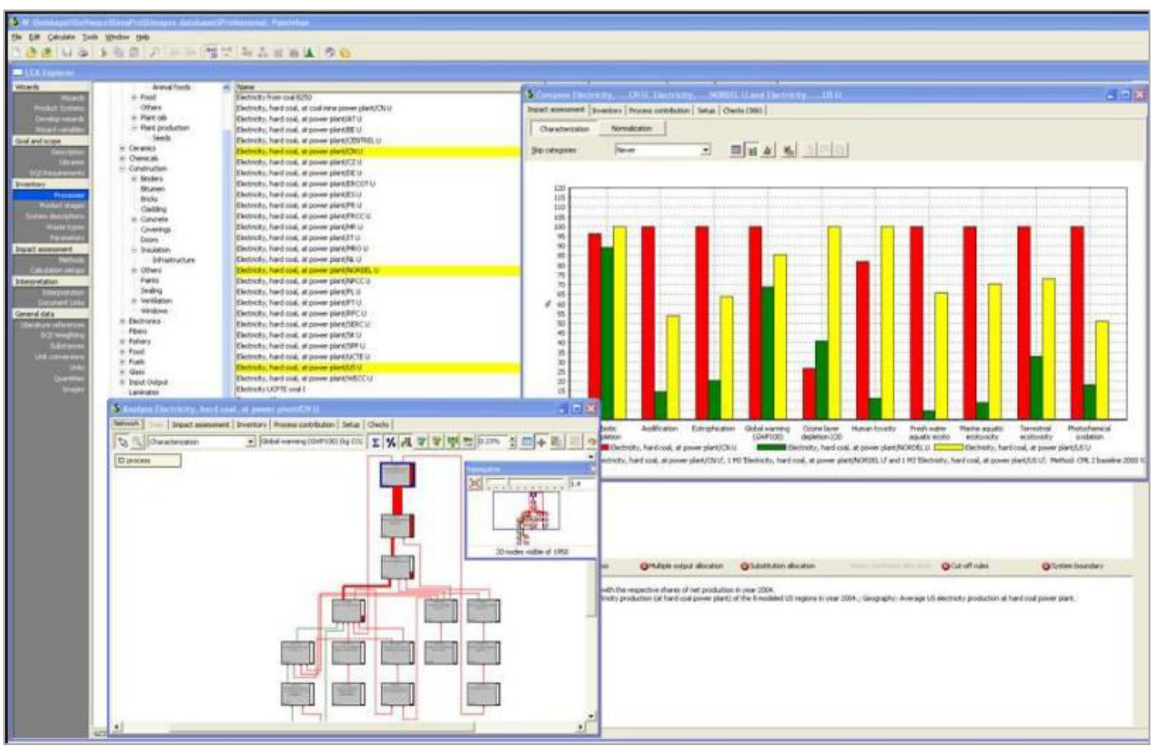

Figure 7: Impact Assessment Results in SimaPro

1.5 Need for the Research

The use of pipes and piping systems can be traced back to ancient times and early civilizations. The prime function of a piping system is to carry fluid from one location to another location. During operational life period, a piping system deteriorates due to various physical and environmental factors like corrosion, erosion and temperature effects. In case of metallic pipes, degradation leads to reduction of pipe thickness due to loss of metal. Depending upon the reduction in thickness, the damaged pipe can either be replaced or repaired. The nature and severity of deterioration will determine whether the pipeline requires replacement or repair [15].

The leakage of oil and gas pipelines has large impact on economy as well as on environment. A leakage of one drop per second can release about 300 gallons of petroleum into the environment annually [16]. Because of this leakage, pressure in the pipelines reduces which allows the contaminants to enter the system which can degrade the quality of fuel being transported [17]. Pipeline leakage increases the energy consumption of the system as more fluid is needed to the leakage point to keep the fluid pressure constant, which is maintained with the help of pumps [18].

Several techniques are used in industry to repair damaged pipes. These techniques include weld buildup, fillet welded patch, flush welded patch, mechanical clamp, non-metallic composite repair system, non-metallic lining of pipe etc. Along with technical and economic concerns, environmental impacts of these techniques should be considered while selecting a repair procedure for a damaged pipe. Also in recent year’s new repair techniques like nonmetallic composite repair is becoming more common. So there is a need to compare these modern techniques with existing ones and provide a guideline for their environmental impacts. This thesis work will apply LCA to four repair techniques used in Saudi Arabian oil and gas industry. The specific objectives of the research project are defined in the following section.

1.6 Objectives

The objectives that have been outlined for this study are as following:

- Construct a LCA model for four different oil and gas pipe repair processes.
- Establish life cycle inventory of each repair process.
- Conduct LCA of each process using SimaPro.
- Interpret results obtained from the life cycle assessment.
- Identify environmental issues in the life cycle of four repair processes.
- Finally provide recommendations for incorporating environmental impacts while making decisions about repair processes.

CHAPTER 2

LITERATURE REVIEW

LCA is an environmental design tool to compare the environmental impact of different products and processes. Several studies have been conducted in the past to investigate and compare the environmental performances of processes. Summary of relevant studies are presented in this chapter.

2.1 Studies Related to Comparative Environmental Analysis

Environmental comparison of two different products is very common in literature. LCA is a comprehensive method to select the environmental friendly process or a product among the different available options. Several studies have been conducted by researchers who successfully investigated the environmental performance of various products and processes. Some of the relevant studies are presented below.

Johnson Werner [9], performed a comparative life cycle assessment of steel and concrete in 2006. Study compared the operational energy of hypothetical structures. Johnson [9] analyzed steel and concrete require to construct 10,000 square feet building in Boston, Massachusetts. 10,000 square-foot area was chosen as a functional unit for the study. Building was considered to be an office structure. Stories were not specified and the system boundaries only included extraction, production, manufacturing and consumption phases. Ecoinvent database was used for inventory analysis.

Analyses was conducted for the energy consumption, carbon dioxide emission and resource depletion for both steel and concrete. Steel has lower resource depletion and carbon dioxide emissions than concrete. However, the energy consumption was found to be the same for both materials as shown in Figure 8. The difference in the resource depletion is more noticeable as compared to other two categories which have small and negligible differences.

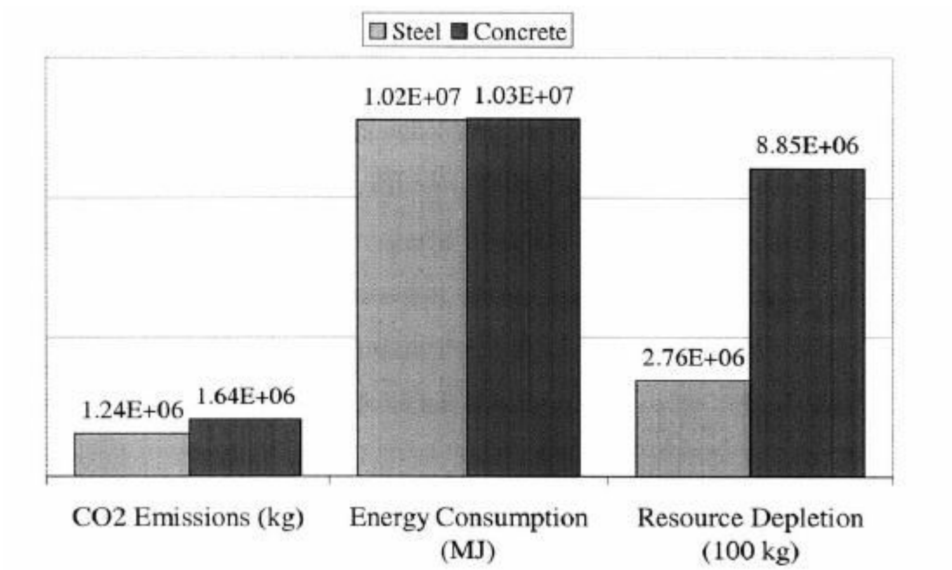

Figure 8: Environmental Comparison of Steel and Concrete [9]

Nicolas and Dorian [19] compared MESO-CLAD (direct additive laser manufacturing) process with conventional machining process through the life cycle assessment. The study was conducted to compare the environmental impacts of laser process with machining process. The life cycle assessment was performed using SimaPro. Eco Indicator 99 methodology [20] was used to carried out the environmental comparison which considered resources, ecosystem quality and human health as an impact categories.

This study predicted that CLAD process is more environment friendly as compared to tradition machining process. The damages to resources and human health for the CLAD process are comparatively very small as compared to machining. According to LCA, 90% of impact in CLAD process is because of powder production [19]. Overall, study revealed that the CLAD process is much more environment friendly as compared to machining process as shown in Figure 9.

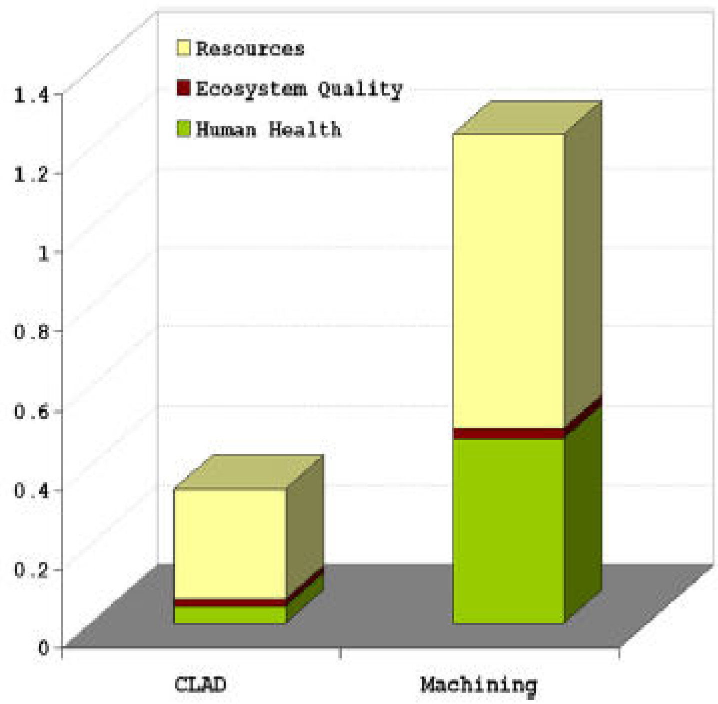

Figure 9: Environmental Comparison Between CLAD And Machining Process [19]

Fu Zhao & William Z. Bernstein [21] compared the environmental performance of laser assisted manufacturing processes with traditional manufacturing processes. The study was performed on two different processes. The laser shock peening process was compared with traditional shot peening.

In the case of peening process, service life of one welded panel was chosen as functional unit. Study revealed that laser shock peening has 45% less environmental impact as compared to shot peening. In the case of turning process, engine cylinder liner was chosen as functional unit. The environmental impact of laser assisted turning was found to 50 % less than conventional turning among all impact categories except eutrophication and ozone depletion.

Scott Unger [22] in 2013 studied the environmental impact of a disposable medical device: dental bur which is commonly used by dentists for examining tooth decay, drill cavities in teeth, tooth structure, fill the cavities. These dental burs can be reused maximum 30 times but rate of use is variable depending upon the personal belief towards reuse [23]. LCA was performed to compare the environmental impact of reused and disposable dental burs. One reusable dental bur was chosen as functional unit. Dental burs were recycled with the help of autoclave and ultrasonic cleaning devices. Three different cases were studied based on the number of dental burs placed in the cleaning devices. In first case, cleaning devices were loaded with 30 burs which was the maximum capacity. In second case, devices were loaded with 20 burs and finally, the devices were loaded with 10 burs. Study concluded that environmental impact was lowest in the first case when cleaning device were fully loaded and impact was largest in the third case when only 10 burs was loaded in the cleaning devices.

Sabina et al. [24] analyzed environmental impact of street light technologies for roads in United Arab Emirates. Two different energy efficient lighting technologies: ceramic halide bulb (CMH) and light emitting diode (LED) were investigated. All the processes from extraction to end of life i.e. from cradle to grave during the life cycle of these two streetlight technologies were modeled in SimaPro. Eco-indicator 99 was used to calculate environmental impact. Both light fixtures were assumed to be manufactured in USA. The parts were transported from Boston, USA to Abu Dhabi by aircraft and then transported to warehouse through trucks.

The average life of 250 Watt CMH bulb is 20,000 h while the average life of 180 Watt LED is 30,000 h [25]. Therefore, 60,000 h (14 years) of operation was chosen as functional unit. It was found that LEDs have higher environmental impact during production stage as compared to its operational stage because of low energy consumption during operation life as shown in Figure 10. Study revealed that LED has the overall lowest environmental impact as shown in Figure 11.

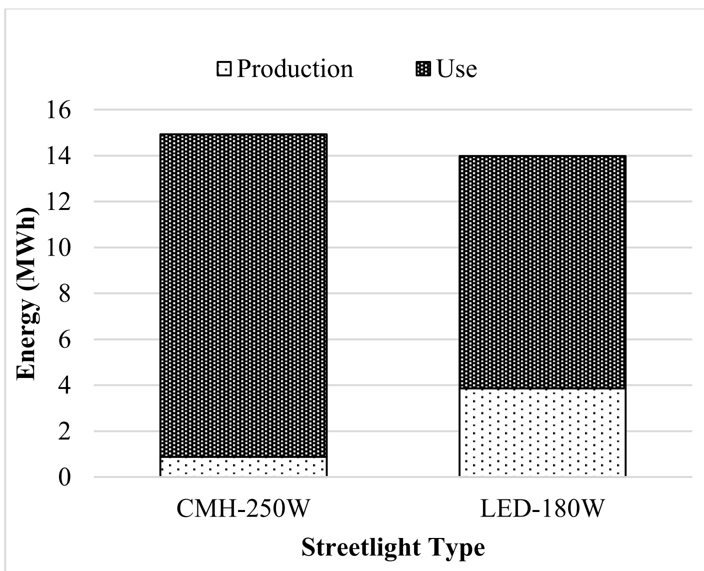

Figure 10: Energy Consumption of Street Lights Powered by Electricity Grid [24]

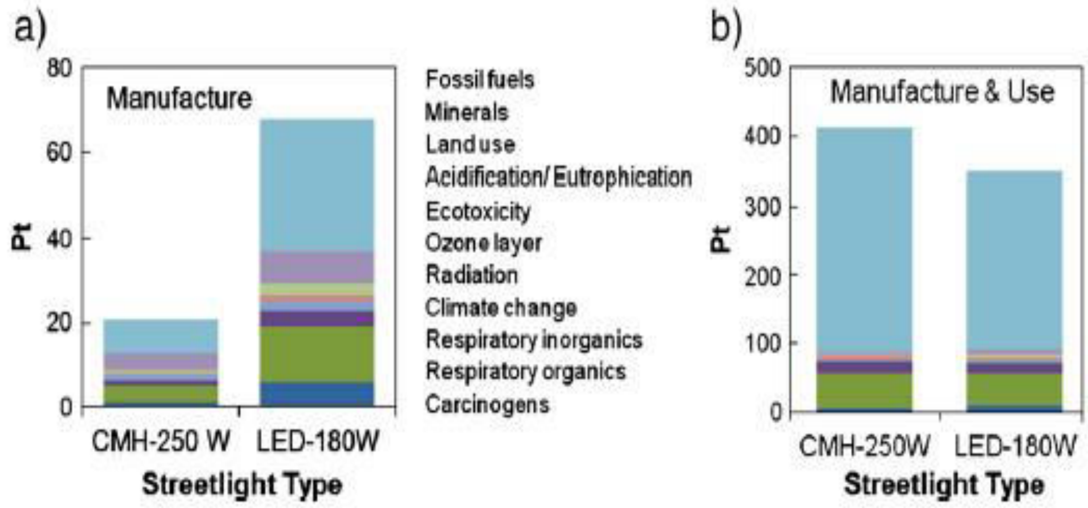

Figure 11: Impact Assessment Results of CMH and LED Lights [24]

Sproesser et al. [26] studied the environmental impact of welding technologies for thick plate welds. Manual metal arc welding (MMAW), laser arc-hybrid welding (LAHW) and gas metal arc welding (GMAW) was used to join the plates. 1 m weld seam was chosen as functional unit. Gabi 6.0 was used to model the life cycle inventory data. CML 2002 method was used to compare the environmental impacts in selected categories global warming potential, eutrophication potential, acidification potential and photochemical ozone creation potential. The results revealed that MMAW has higher environmental impact as compared to GMAW and LAHW as depicted in Figure 12. It was found that environmental impact of MMAW was higher due to higher material and electricity consumption.

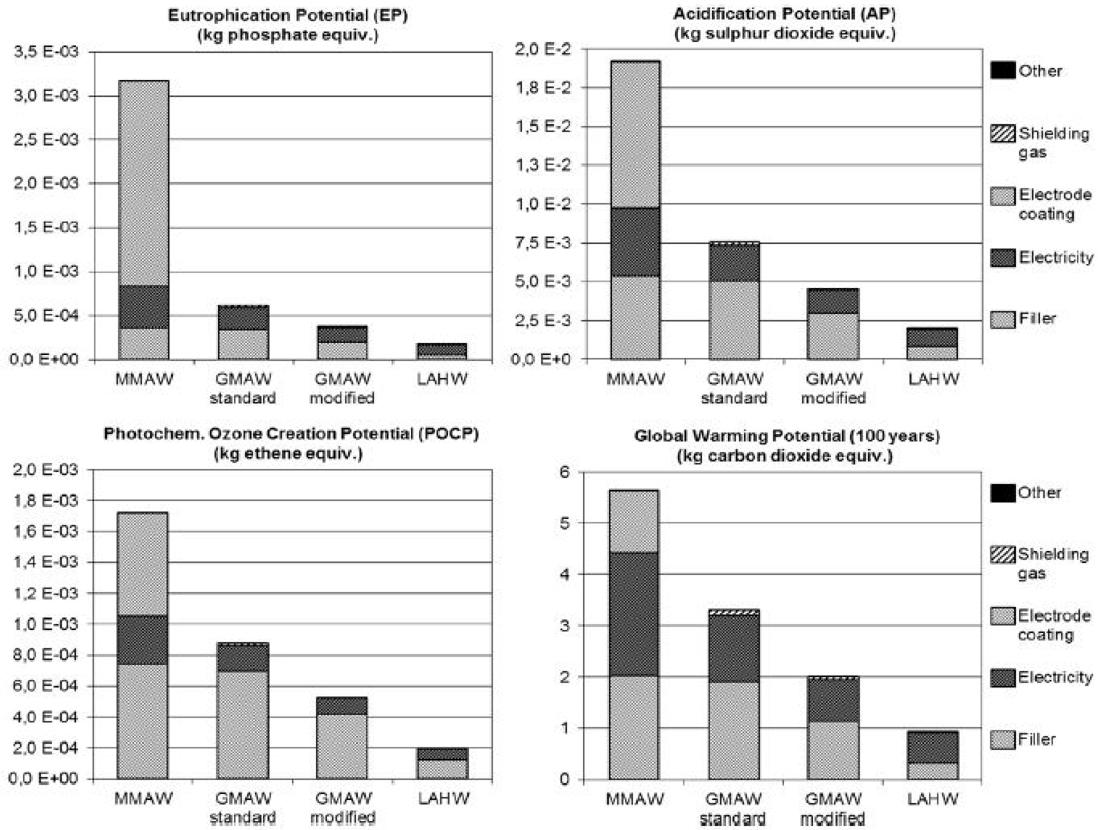

Figure 12: LCA Results of Welding Process [26]

Within the scope of study, LAHW was found to be most superior solution due to the high performance and low weld volume. Finally, Sproesser et al. [26] recommended that GMAW and LAHW should be used for thick plates weld. However, if economic condition allows, LAHW should be preferred.

2.2 LCA of Repair Processes

Maxineasa et al. [27] performed LCA of reinforcement of concrete beam with various carbon fiber reinforced polymer flexural strengthening techniques. Six case studies were considered with different fiber reinforced polymer (FRP) dimensions. Environmental impact was calculated using Gabi 6.0. Analyses was conducted for the climate change, human toxicity and ozone depletion.

It was found that high load capacity could be achieved by using carbon fiber strengthening scheme at the cost of high environmental impact. Furthermore, the use of carbon fiber material in different dimensions also reduced the environmental impact significantly [27]. Therefore, study concluded that the usage of composite materials can represent an important step towards the sustainable development of the construction sector.

Stavros Drakopoulos et al. [28] studied the environmental impact of cutting and joining processes taking place during repair of ship hull. These processes included oxy-acetylene cutting, plasma arc cutting, shielded metal arc welding, flux core arc welding and submerged arc welding. Life cycle inventory data was modeled using SimaPro 6.0. Impact was calculated with the help Eco-Indicator 99. All the parameter was estimated for 1 meter of cutting and welding.

In the case of welding process, results showed that flux core arc welding (FCAW) is 70 % more hazardous as compared to shielded metal arc welding (SMAW) than and 50 % more than submerged arc welding (SAW) [28]. Whereas, in the case of cutting process, plasma arc cutting (PAC) has negligible environmental impact as compared to oxy-acetylene cutting (OAC) as depicted in Figure 13 and 14. Overall, study revealed that SAW and PAC was more environmental friendly as compared to SMAW, FCAW and OAC.

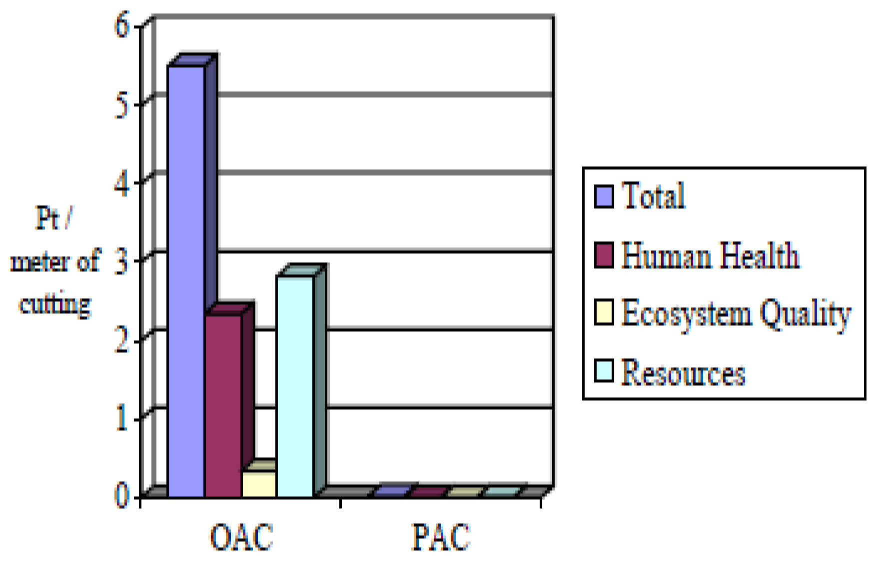

Figure 13: Environmental Impact of Ship Hull Repair Cutting Process [28]

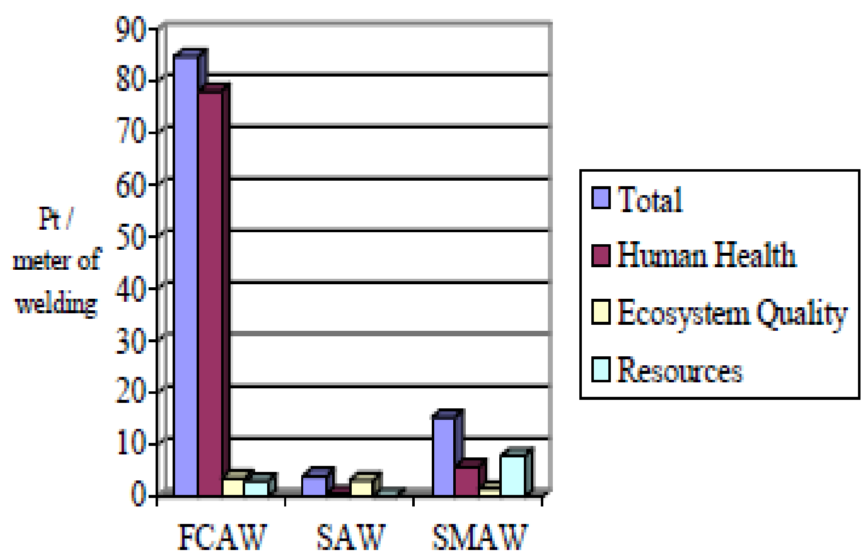

Figure 14: Environmental Impact of Ship Hull Repair Welding Process [28]

2.3 LCA Related to Welding Processes

Welding is one of the most important joining process used in manufacturing industry and for repair. Recently studies show that welding process has large contribution in polluting the environment. Some of the studies are presented showing the potential of welding for degrading the environment.

Whenever, welding is performed, ultimately pollutant gases, fumes and dust will be sent to the environment by some means [29]. In arc welding process, about 0.5 to 1% of all consumables are converted into pollutant gases, dust and fumes. In UK, 700 ton/ year of welding pollutant are released in environment [30].

Many welding processes are used for the repair of oil and gas pipelines. Weld metal buildup and fillet welded patch are welding repair techniques used to repair the defected portion of pipe according to the instruction given in ASME PCC-2 standard [31]. Selection criteria of repair and testing procedures are also stated by ASME PCC-2 standards.

Welding processes are major source of energy consumption and greenhouse gas emission [32, 33]. Environmental impact of welding processes has been studied in different ways. Yeo and Neo [29] developed a model for the selection of welding processes. Later, Chein [34] extended the scope to joining of aluminum sheet. These above studies were evaluated on basis of greenhouse gas emission, cost and performance standards. However, processes are not evaluated in depth in these studies and the main focus of these studies was on decision support oriented system [26]. Detail assessment of welding processes energy consumption, welding fumes estimation etc. was studied by Bosworth [35].

Laser welding with improved efficiency was studied by Wei in 2015 [36]. Pohlmann et al. [37] calculated welding fume generation rate for variety of processes. Environmental impact of welding waste material like electrode or stubs and fume generation was recently studied by Vimal et al. [38] and Zukauskaite et al. [39]. Vimal et al. [38] calculated life cycle impact of manual metal arc welding process and proposed the best disposal scenario. Zukauskaite et al. [39] compared welding processes used in ship industry and suggested submerged arc welding as environmentally friendly process because of low fume generation. Drakopoulos [28] presented the same conclusion and favored submerged arc welding process for repair of ship hull. Researcher considered filler and shielding gas for MMAW, flux cored arc welding and submerged arc welding. However, detailed view of process inputs and outputs was not the part of their work. Above studies clearly showed that welding processes have large impact on environment. For this reason, environmental impact of repair processes that involve welding should be estimated.

The cited studies demonstrate the effectiveness of LCA methodology to compare the environmental impact of various products and processes. Furthermore, it is shown that steel, composite materials and welding processes have impact on the environment.

CHAPTER 3

RESEARCH METHODOLOGY

The objective of this research is to investigate environmental impacts of repair processes commonly used in oil and gas industry. This research can be used to highlight the environment degradation potential of repair processes. Moreover, analysis would be helpful for selecting environmental friendly repair process. This chapter will describe four repair processes that were selected for the study.

3.1 Pipe Repair Processes

Several repair methods are used in oil and gas industry depending upon the type and size of defect. Selection of repair techniques is very important step and need special considerations. According to ASME PCC-2, there are more than 10 repair techniques in current study. Following assumptions has been made for the defect.

- Defect is considered to be local wall thinning due to corrosion.
- Defect size < 0.5 D
- Application is considered to be on-shore pipeline repair.

Table 1: Guideline for Selection of Repair Techniques [31]

No	Title	General Wall Thinning	Local Wall Thinning	Pitting	Blisters	Cicumferential cracks
1	Butt Welded Insert plates	Y	Y	Y	Y	Y
2	Weld Build Up	N	Y	Y	N	N
3	Seal welded threaded connections and seal weld repair	NA	NA	NA	NA	NA
4	Welded leak box repair	N	Y	Y	N	N
5	Full encirclement steel reinforcing sleeves	Y	Y	Y	N	N
6	Fillet Welded patches	N	Y	Y	S	N
7	Welded plug repairs	N	Y	Y	N	Y
8	Mechanical Clamp	N	Y	Y	N	R
9	Damaged Anchor in Concerete	NA	NA	NA	NA	NA
10	Non Metallic composite repair system	Y	Y	Y	Y	Y
11	Non Metallic Internal lining of Pipe	Y	Y	Y	Y	Y

Where,

Y = generally appropriate

R = may be used, require special cautions

N = not generally appropriate

NA = not applicable

Weld build up, fillet welded patch, mechanical clamp and composite overwrap can be used for repairing the local wall thinning defect as shown in Table 1. The last two conditions mentioned above are validated by consulting the oil and gas pipeline repair experts. The dimensions of pipe for experiment are shown in Table 2 and Figure 15.

Table 2: Pipe and Corroded Surface Size [40]

Outer diameter (D)	168.3 mm
Inner diameter (d)	154.4 mm
Length of pipe (L)	1000 mm
Groove length	60 mm
Groove width	20 mm
Groove depth	2.5 mm

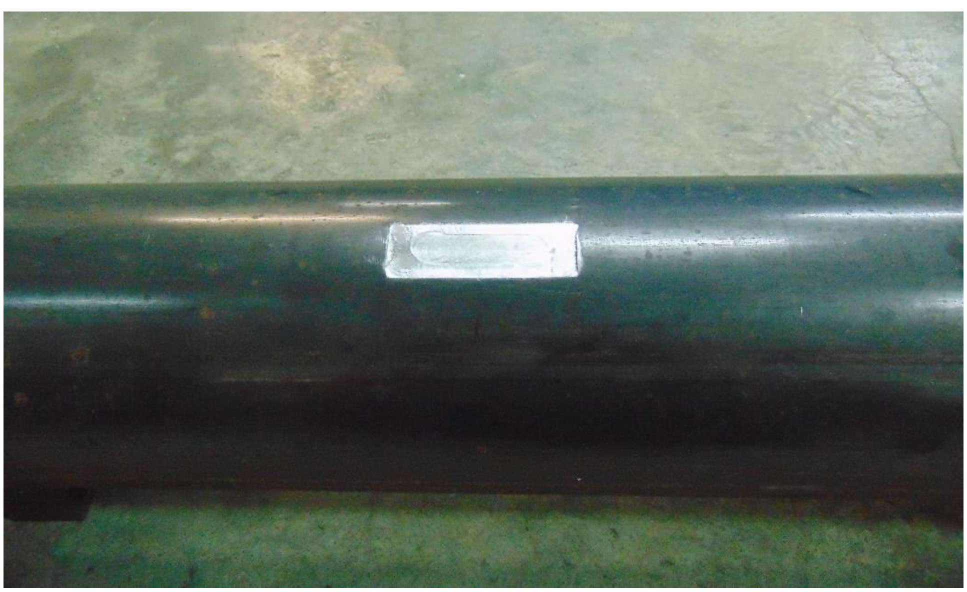

Figure 15: Pipe Defect

The details of above mentioned repair techniques will be discussed in the experimentation section at the end of this chapter.

3.2 Pipe Repair LCA

This section will explain the goal and scope of this analysis, function unit, data collection and impact categories.

3.2.1 Goal of LCA Study

The goal of this research is to calculate and compare the environmental impact of four repair processes used in oil and gas industry. The intended application of the LCA study is to recommend environment friendly repair process. Hence, the target audience is considered to be industrial experts and researcher.

3.2.2 Scope of LCA Study

In order to compare the oil and gas repair processes, life of repair process is considered as the functional unit (FU). Cradle-to-gate LCA is considered which include extraction of material and production/ manufacturing stages of LCA. System boundaries of repair processes in line with goal and scope are shown in Figure 16. The study is conducted with the specific focus on Saudi Arabia. However, the composite repair and mechanical clamp products are manufactured in United States and Turkey respectively. In order to ensure the data quality, repair is performed experimentally in the lab.

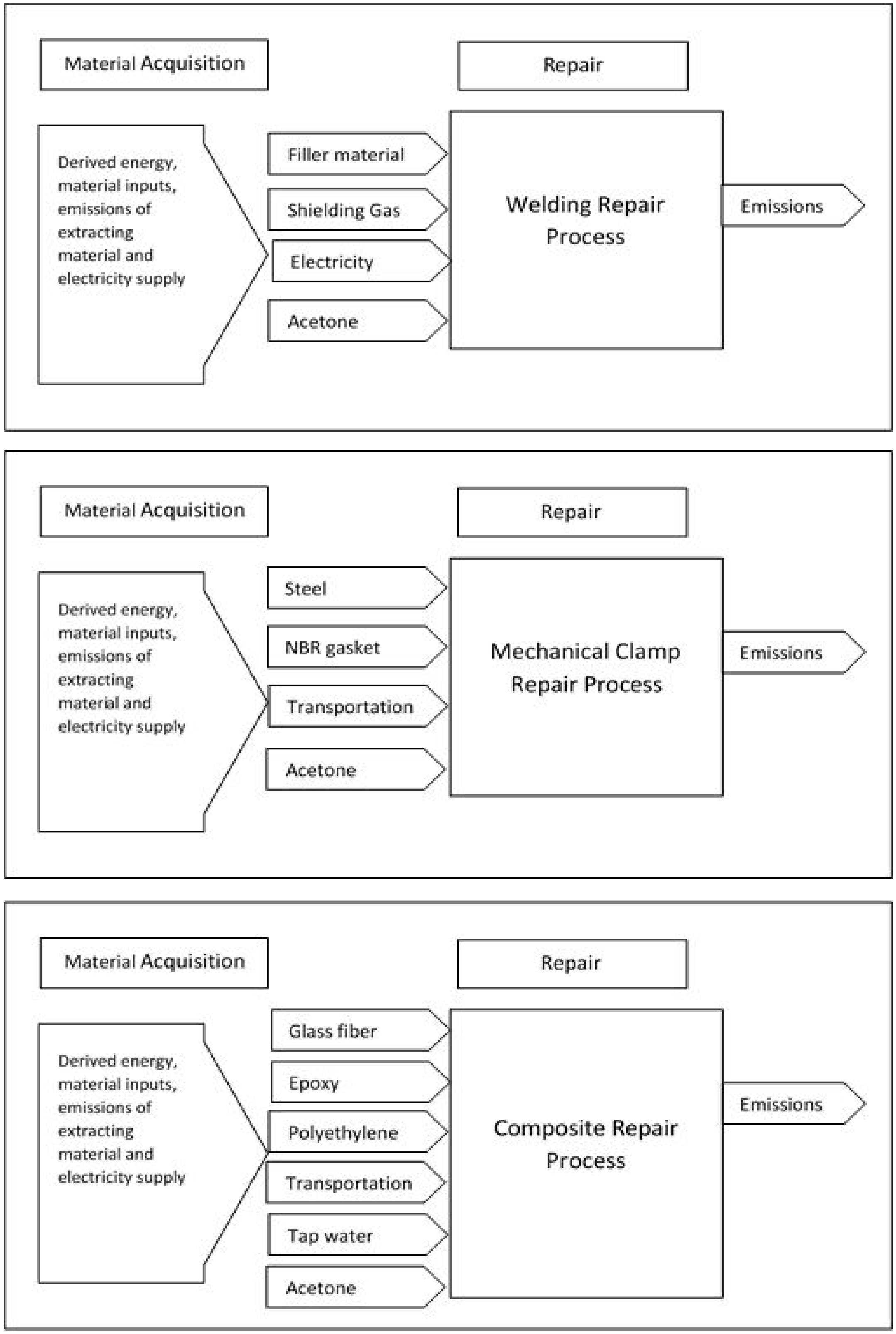

Figure 16: System Boundaries of Repair Processes

3.2.3 Inventory Data

Based on information collected through industry and industrial experts, repair processes were performed in lab and inventory data was collected. The detail of experimental program is mentioned in the following section. The repair processes were performed according to instructions given in ASME PCC-2 [31].

- In case of composite overwrap, same material is used as in oil and gas industry. Complete composite repair solution is imported from United States. Composite is wrapped over pipe with the similar methodology as practiced by oil and gas companies and corresponding data is noted.
- Mechanical clamp for oil and gas pipeline is imported from Turkey. The inventory data is collected from manufacturer of clamp.
- In fillet welded patch, steel plate is welded on defected pipe. Filler material and gas consumed in welding process is measured from weighing balance. Electricity consumption is calculated by measuring current and voltage values during welding.
- In the last repair method, metal is deposited onto the pipe according to ASME PCC-2 as mentioned in previous chapter. The filler material and gas consumption was measured through weighing balance whereas, electricity data is measured in the same way as that of fillet welded patch.

3.2.4 Life Cycle Impact Assessment

After collecting the life cycle inventory data, life cycle impact was calculated with the help of SimaPro [41]. CML (Centre of Environmental Sciences) method is used for life cycle impact assessment. The impact categories under consideration are abiotic depletion, abiotic depletion (fossil fuel), global warming potential, ozone depletion potential, human toxicity, fresh water aquatic ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification potential and eutrophication potential. The detail of impact categories is as follows

- **Depletion of Abiotic Resources**

The impact category is pertained with protection of ecosystem health and human health. The impact category indicator measures the emissions related to extraction of minerals and fossil fuels. Abiotic Depletion Factor (ADF) is determined for each extraction of minerals in kg Antimony equivalents/kg extraction. For extraction of fossil fuel, it is calculated in MJ equivalents.

- **Ozone Depletion**

Ozone depletion (OD) impact category is measure of reduction in stratospheric ozone layer thickness which allows the UV rays to approach earth surface [6]. This can have catastrophic effect on living species and ecosystem. It is measured in kg CFC-11 equivalent/kg emission

- **Acidification (AP)**

It is a potential for emissions to increase the acidity of soil and water. Acid rain is one of the well-known effect, which can corrode the built environment, damage forest and acidify soil and water. The major contributor to acid rain are SO_2 and nitrogen oxides from fossil fuel combustion. This category is expressed as kg SO_2 equivalents/ kg emissions.

- **Global Warming Potential**

Global Warming Potential is related to emission of greenhouse gases and it is defined for time horizon of 100 years in kg CO_2/ kg emission.

- **Eutrophication**

Eutrophication refers to addition of chemical nutrients to surface waters, which promotes the excessive growth of plant life such as algae. Algae can deplete the water of its available oxygen which leads to the death of aquatic life. The major drivers of eutrophication are phosphorous and nitrogen compound from fertilizer. It is expressed in kg PO_4/kg emission.

- **Fresh Water Aquatic Ecotoxicity**

This refers to potential of an emission to cause harmful effect on fresh water ecosystem. It is expressed in 1,4-dichlorobenzene equivalents/kg emission.

- **Marine Ecotoxicity**

This refers to impacts of toxic substance on marine ecosystem and expressed in 1,4-dichlorobenzene equivalents/kg emission.

- **Terrestrial Ecosystem**

This category is concerned about the effect of toxic substances on terrestrial ecosystem and expressed in 1,4-dichlorobenzene equivalents/kg emission.

- **Human Toxicity**

Human toxicity is related to effect of toxic substance on human environment as a result of emission of toxic substances into soil, air and water. It is measured in 1,4-dichlorobenzene equivalents/kg emission.

- **Photochemical Oxidation**

The formation of reactive substances (mainly ozone) which are injurious to human health and ecosystem and may also damage the crops. Photochemical oxidation potential is measured in kg ethylene equivalents/kg emission.

3.3 Experimental Data Collection

According to ASME PCC-2 standard, four repair techniques were performed experimentally. The details and guidelines of processes as per ASME PCC-2 will be further explained next:

3.3.1 Fillet Welded Patch

The local flaws can be repaired by fillet welding a circular or a square patch to the pipe. The repair plate is sized to cover the damaged areas. The patch may be of the same material as of the pipe or of a higher grade material. This repair technique is used for small defects, local wall thinning due to erosion and corrosion on the pipelines having hoop stress less than 20 % of yield stress. This repair method is not limited by the component size.

According to ASME PCC-2 [32], the weld patch should meet following requirements:

1. The method is applicable to pipelines, cylindrical and conical vessels.
2. Patch material and welding filler metal should be the same or very similar to base material.
3. The thickness of patch plate is dependent on material's mechanical properties.

4. The length and width of patch is governed by the requirement that welds should be located on base metal encompassing the damaged area.
5. The patch plate should overlap base metal by at least 25 mm.
6. Parts to be fillet welded should be fit as tightly as possible to the welded surface.
7. Welding procedure should be qualified according to the requirement.
8. Paint, scale, rust and other foreign material must be removed from weld zone.

The dimensions of the steel plate depends upon the size of crack and it is calculated according to ASME PCC-2 standard [31] as mentioned above. The dimensions of steel plate are shown in Table 3. Gas Tungsten Arc Welding (GTAW) is used for welding steel plate onto the surface of pipe as shown in Figure 17.

Table 3: Steel Plate Size in Fillet Welded Patch [31]

Dimension	Size
Length of patch	98.14 mm
Width of patch	38.14 mm
Thickness of patch	3 mm

Figure 17: Fillet Welded Patch-Experimental

3.3.2 Weld Build Up

It is also referred as direct weld deposit. This method is used for the repair of piping component degraded by wall thinning due to external corrosion. Specifically, weld build up method is used to restore steel (carbon, low alloy, or austenitic stainless steel) structurally to avoid the replacement. Gas Tungsten Arc Welding (GTAW) is used for metal buildup. ASME PCC-2 is followed for the geometry of buildup patch.

Following requirements should be met for buildup patch:

1. The chemistry of deposited weld metal should match the base.
2. The tensile strength of deposited weld metal should be at least equal to or greater than the tensile strength of base metal.
3. The weld deposit should extend in each direction beyond the affected portion of base metal by distance B as shown in Figure 18.

$$B = \frac{3}{4}\sqrt{Rt_{nom}}$$

Where,

R = Outer radius of the component, or $\frac{1}{2}D$

t_{nom} = Nominal wall thickness of the component

4. The thickness of the buildup should not exceed the thickness of pipe
5. The thickness of buildup should be relatively uniform
6. The finished buildup should be circular, oval, full circumferential or rectangular in shape as depicted in weld buildup profile shown in Figure 19.

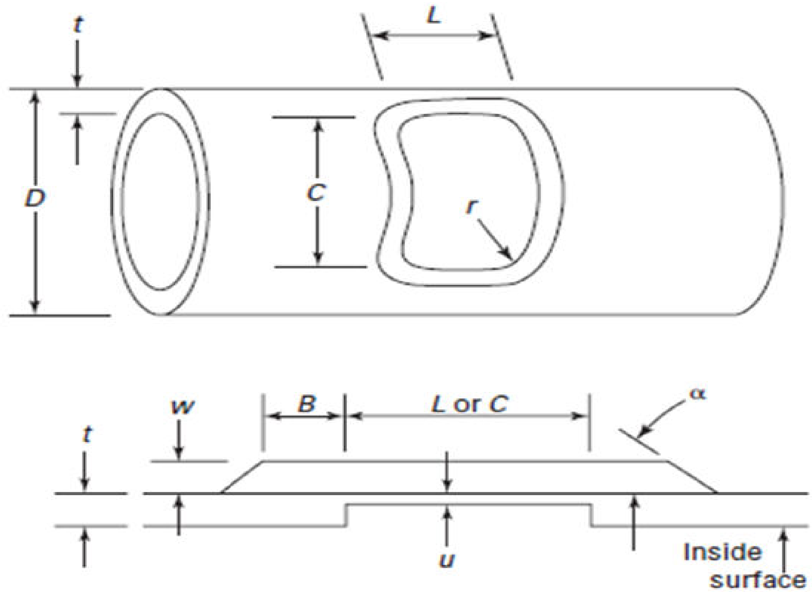

Figure 18: Geometrical Dimension of Weld Build Up [31]

Figure 19: Weld Build Up

According to ASME PCC-2, the dimension of buildup patch is shown in Table 4.

Table 4: Geometry of Weld Buildup [31]

Dimension	Size
Length of patch	98.14 mm
Width of patch	38.14 mm
Thickness of patch	3 mm

3.3.3 Mechanical Clamp

Mechanical clamp consists of two shells that are bolted to a damaged pipe as shown in Figure 20. Repair clamps have the variety of shapes e.g. cylindrical, rectangular and with either flat or formed heads. Mechanical clamps normally used to seal the leaking component or to reinforce the damaged component. Clamps can also be welded to the pipe if required. The annular space between the clamp and pipe can be left empty or sealant is used to cure and seals the leak.

Figure 20: Mechanical Clamp

Generally, the material of the construction of clamp should be similar to the base material of repaired component or pipe. But clamps with the different material is also acceptable if they are compatible with the process and existing component. The design life of the repair shall be based on the remaining strength of pipe, mechanical properties of clamp and its sealant element [31].

Following are the factors that can cause the failure of clamp:

1. If external components like flange, bolts, are in contact with the leaking fluid so it can significantly degrade or corrode.
2. As the temperature of clamp can be lower than the component, condensate from leakage should be considered for corrosive effects.
3. The clamp can cause the component to run at different temperature which can increase the corrosion rate.
4. Insulating effect of clamp may increase the temperature of encapsulated bolting, causing it to yield
5. Residual stresses due to the differential expansion can cause the clamp to leak.

The installation and design parameter of clamp should include the following considerations [31]:

- The clamp length should be such that will extend over the sound area of repaired pipe.
- There should sufficient wall thickness at the contact point to carry the pressure and structural loads in the component.
- The annulus pressure of injected sealant should be considered because it can cause the inward collapse of clamped component.

- Before the installation of clamp, surface should be cleaned from the corrosion deposits, dirt, paint, and insulation.

3.3.4 Composite Overwrap

Recently non-metallic materials are also being used for the repair of oil and gas pipes. Composite overwrap reinforces the corroded section of the pipe. Composite overwrap referred to a family of fiber glass products used to repair defects in pipes, ductile fractures in high pressure gas pipelines and reinforce other mechanical defects. Composite overwrap provides a permanent reinforcement for the corroded pipe and proper installation will restore full strength in the repair zone.

In addition to permanent structural repair for external defects, composite overwrap may also be used for the temporary reinforcement of internal corrosion. Composite overwrap does not control the corrosion or stop it. The life of repair in case of internal corrosion will depend upon the growth rate of the defect.

The dimensions of composite overwrap is calculated according to ISO TS 24817 [42] as follows.

For the slot type defect:

$$l_{over} = 2\sqrt{Dt}$$

Where,

l_{over}= extended length of composite beyond the defect length in one direction

D = outer diameter of pipe

t = thickness of pipe

The total axial length of the composite will be

$$l_{total} = 2l_{over} + l_{defect} + l_{avaliable}$$

According to ISO TS 24817, $l_{available}$ i.e. available length is fixed is about to be 25 mm. Hence, the total length of composite required and number of wraps and relevant data is shown in Table 5.

Table 5: Pipe Wrap Specifications for Defected Portion

Length of composite	243 mm
Number of wraps	8

To insure the quality of composite overwrap, the installation of composite over the pipe must be done under great care. The installation procedure for the pipe is stated as below,

- Characterize the defect to determine whether composite overwrap is a suitable solution or not.
- The length of the defect will determine the no. of wraps needed for repair. As a rule, composite must overlap the defect by 2- inches on each side.
- Surface is prepared for repair by using acetone to remove residues, primer, or adhesive. Four to six inches' area on each side of defect should be cleaned.
- Attach the 2-3 wraps just for the positioning purpose. Center the wraps over the repair portion ensuring 2-inch overlap on the either side of the defect. Mark the edges of wrap as a reference.

- Apply the filler material to all voids, both edges of longitudinal weld and on one edge of starter pad. Ensure sufficient filler material is applied to provide the contact between prepared pipe surface and composite to be installed.
- Measure the equal parts, by volume of adhesive material. Pour mixed adhesive into application tray. Mix thoroughly and allow the material set for 10-20 minute before applying to the pipe surface as shown in Figure 21.

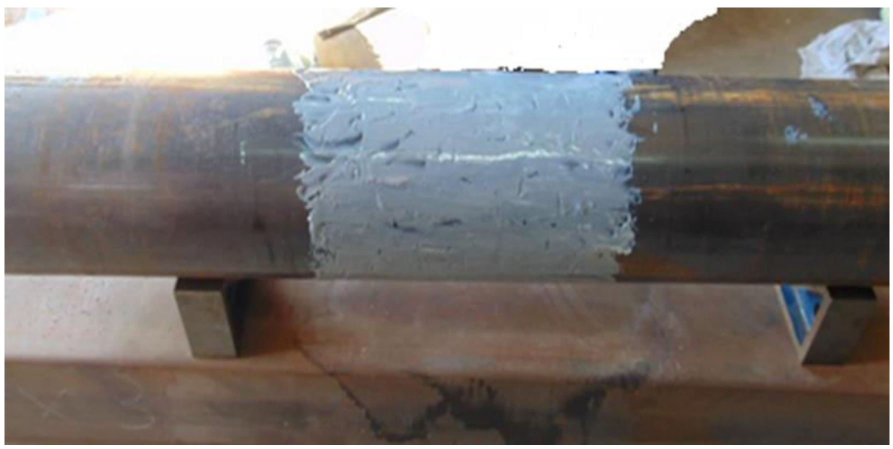

Figure 21: Coating of Adhesive on Pipe Repair Surface

- When ready to use, remove the roll from foil pouch and submerse in the water for approximately 2 minutes.
- Begin wrapping around the pipe surface (repair zone) while applying the uniform tension as shown in Figure 22.
- Ensure that point is marked where the leading edge of composite wrap will be positioned. Filler is required to make contact at the point where the first layer of composite wrap overlays the second.

Figure 22: Pipe Wrap

- When material has overlapped itself, begin pulling tightly during the remainder of application. Thoroughly saturate each layer of material with water during application.
- After finishing wrap application, 4-6 layers of constrictor wrap is applied tightly extending over the repair surface. Perforate the surface of compression/constrictor wrap as shown in Figure 23.

Figure 23: Application of Constrictor Wrap

- Allow to cure for 2 hours. System will appear to bubble through perforation. Remove the constrictor wrap. System will continue to degas after being hardened for several more hours.
- Measure equal parts, by volume of adhesive materials in a tray. Mix thoroughly and allow material to set 10-20 minute before applying to pipe surface again as shown in Figure 24.

Figure 24: Final Coating of Adhesive on Pipe Wrap

The life cycle inventory data related to these processes and impact assessment will be presented in the following chapter.

CHAPTER 4

RESULTS AND DISCUSSION

The life cycle assessment of oil and gas pipeline repair processes is carried out using SimaPro [41]. CML is used as an impact assessment method. The method was developed by the group of scientist from Leiden University. It was presented as a midpoint approach methodology to analyze the environmental impact in 2002 [13]. The CML method was based on the problem-oriented approach and includes impact categories: Abiotic depletion, abiotic depletion (fossil fuel), global warming potential, ozone depletion potential, human toxicity, fresh water aquatic ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification potential and eutrophication potential. The oil and gas pipelines repair processes are evaluated for these impact categories. The details of environmental impacts of repair processes will be discussed in upcoming sections.

4.1 Life Cycle Inventory (LCI)

4.1.1 Weld Buildup

Gas Tungsten Arc Welding (GTAW) is used for metal buildup on carbon steel pipe as shown in Figure 25. The dimensions of buildup patch is calculated according to ASME PCC-2 [31] standard and is mentioned in Chapter 3. The detail of Life Cycle Inventory in shown in Table 6.

Figure 25: Weld Build Up

Table 6: Life Cycle Inventory Data of Build Up

Inventory	Material/ Processes	Consumption	Country of Origin
1- Filler metal (g)	Carbon Steel	250	Local
2- Shielding gas (g)	Argon	453.6	Local
3- Cleaning agent (ml)	Acetone	50	Local
4- Energy consumption (kWh)	Electricity	0.324	Local

Life cycle data is modeled in SimaPro. The process layout is shown in Figure 26 which involves all the processes, materials and energy used during weld buildup repair process.

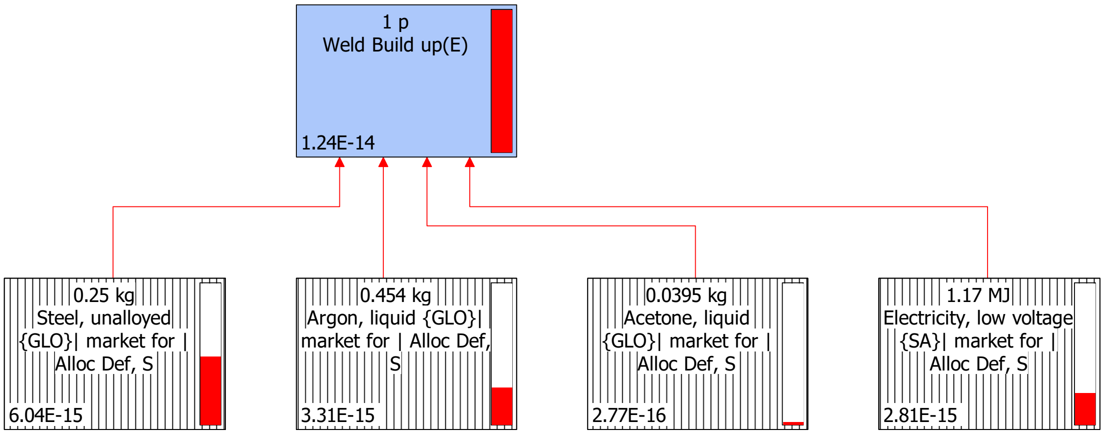

Figure 26: Process Layout of Buildup

4.1.2 Fillet Welded Patch

Welding characteristics e.g. GTAW etc. are same as that of weld build up process. Steel plate is welded on to surface of pipe through GTAW to provide the reinforcement as shown in Figure 27.

Figure 27: Fillet Welded Patch

The detail of Life Cycle Inventory for fillet welded patch is shown in Table 7.

Table 7: Inventory Data of Fillet Welded Patch

Inventory	Material/ Processes	Consumption	Country of Origin
1- Patch material (g)	Carbon Steel	65	Local
2- Filler metal (g)	Carbon Steel	6	Local
3- Shielding gas (g)	Argon	226.8	Local
4- Cleaning agent (ml)	Acetone	50	Local
5- Energy consumption (kWh)	Electricity	0.128	Local

Fillet welded patch also involved the filler material consumption but is comparatively very low as compared to weld buildup process. Overall, material consumptions in fillet welded process related to GTAW welding process are low about 60% than build up process. The process is modeled in SimaPro and layout for this process is shown in Figure 28.

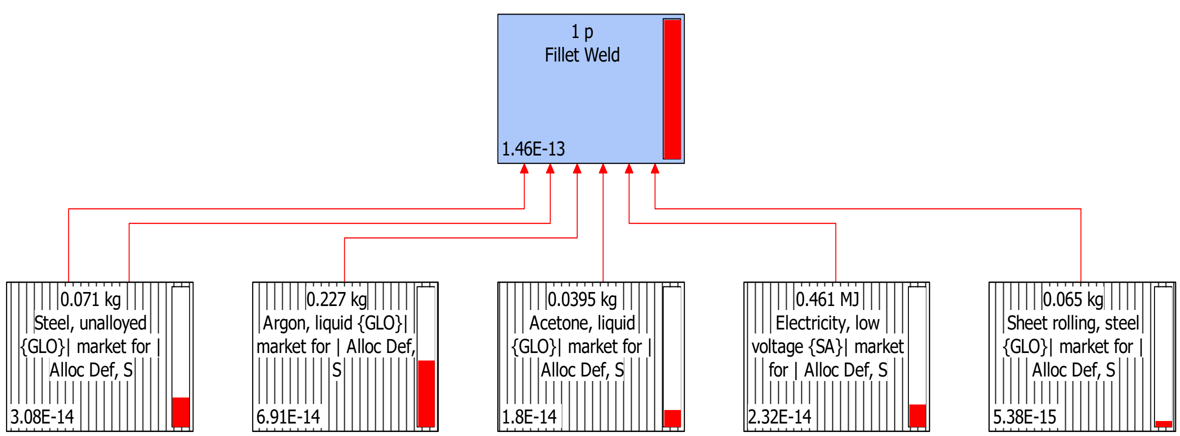

Figure 28: Process Layout for Fillet Welded Patch

4.1.3 Composite Overwrap

Non-metallic composite repair process is a modern repair technique commonly used currently in oil and gas industry. The dimensions of composite overwrap is calculated according to standard ISO TS 24817 [42] as described in chapter 3. Composite overwrap repair technique involves the wrapping of fiber glass on to the surface of defected pipe as shown in Figure 29. The materials and processes used in repair process is mentioned in the Table 8.

Figure 29: Pipe Wrap

Table 8: Life Cycle Inventory for Composite Overwrap

Material/ Processes	Consumption	Country of Origin
Glass fiber (g)	1600	USA
Epoxy (g)	188	USA
Polyethylene (g)	10	USA
Water (g)	6000	Local
Acetone (ml)	100	Local
Transportation (tkm)	61.6	USA

Glass fiber is wrapped over the surface of pipe according to per instructions of manufacturer as explained in chapter 3. The process layout of composite overwrap is shown in Figure 30, depicting the contribution of material and transportation in the process.

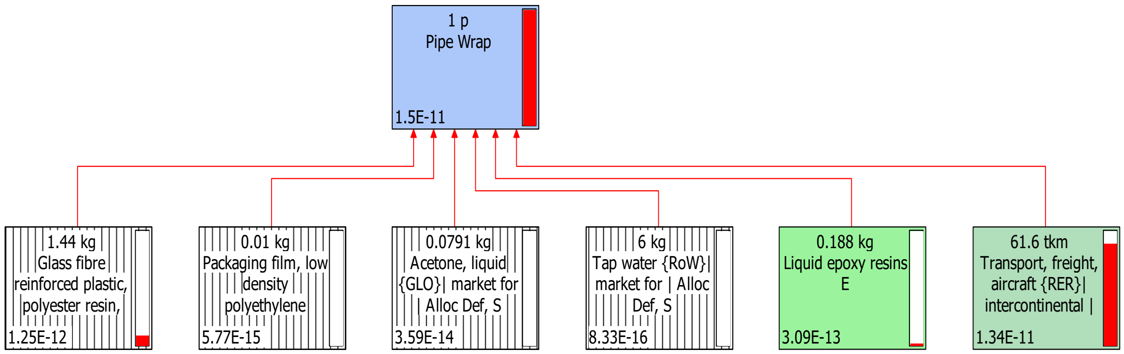

Figure 30: Process Layout of Pipe Wrap

4.1.4 Mechanical Clamp

Mechanical clamp is one of the easiest repair methods which is very easy to install. The pipe with mechanical clamp is shown in Figure 31.

Figure 31: Mechanical Clamp

The clamp material should be compatible with the pipe base material or should be same. The material used for the repair of pipe using mechanical clamp process is shown in Table 9.

Table 9: Life Cycle Inventory of Mechanical Clamp

Material/ Processes	Consumption	Country of Origin
Steel (g)	3120	Turkey
NBR gasket (g)	750	Turkey
Acetone (ml)	100	Local
Transportation (tkm)	13.2	Turkey

The process layout of mechanical clamp repair process is shown in Figure 32, depicted the contribution of each material in process.

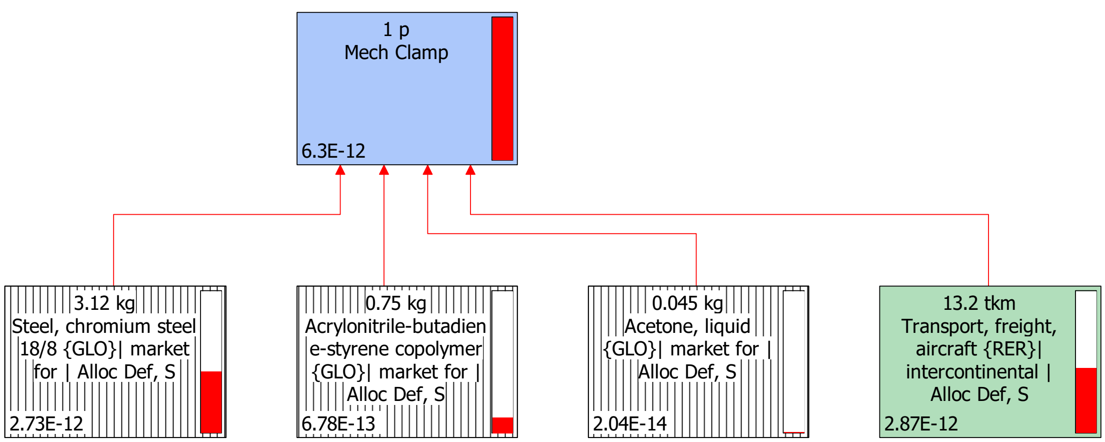

Figure 32: Process Layout of Mechanical Clamp

4.2 Environmental Impacts of Repair Processes

In this section, environmental impacts of four oil and gas pipe repair processes are presented. CML is used as an impact assessment method. Impact assessment was performed in SimaPro 8.05. The results for following impact categories abiotic depletion, abiotic depletion (fossil fuel), global warming potential, ozone depletion potential, human toxicity, fresh water aquatic ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification potential, and eutrophication potential are shown below:

4.2.1 Abiotic Depletion

This impact is related to effect of extraction of minerals on human health and ecosystem balance. Abiotic depletion potential (ADP) is measured in terms of kg Sb/kg emissions and plotted on log scale for each repair process as shown in Figure 33 which shows the contribution of electricity, transportation and material in abiotic potential.

Mechanical clamp has the largest environmental impact as compared to other repair techniques whereas, fillet welded patch has the least environmental impact. Within each repair technique, materials are most contributing in ADP. However, transportation also have significant impact in composite repair technique. Whereas, in case of welding repair techniques (fillet and build up) electricity consumption also have small contribution. Overall, the impact of weld buildup and fillet welded patch is very small as compared to mechanical clamp and pipe overwrap process.

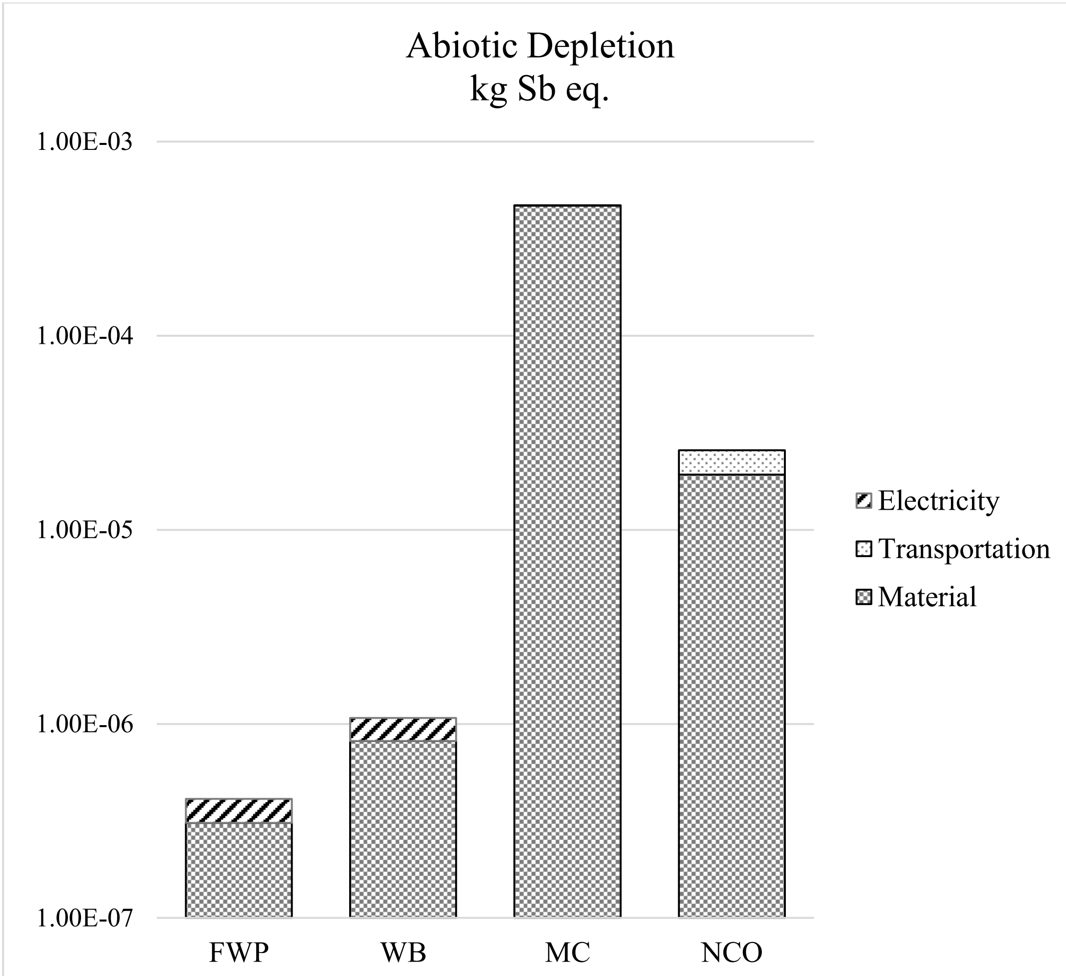

Figure 33: Abiotic Depletion

4.2.2 Abiotic Depletion (Fossil Fuels)

This impact is related to effect of extraction of fossil fuels on human health and ecosystem health. Abiotic depletion potential (fossil fuel) is calculated in MJ and plotted on logarithmic scale as shown in Figure 34.

Composite overwrap has highest abiotic depletion potential as compared to other repair processes whereas, fillet welded patch has the least contribution. The transportation of composite overwrap dominates the impact. Mechanical clamp has also significant impact however, it is slightly less than composite overwrap in which material and transportation have almost equal contribution in abiotic depletion potential (fossil fuel). In the case of weld buildup and fillet welded patch, materials have higher impact than energy consumption however, overall welding repair processes has comparatively less contribution to abiotic depletion (fossil fuel) impact category as shown in Figure 34.

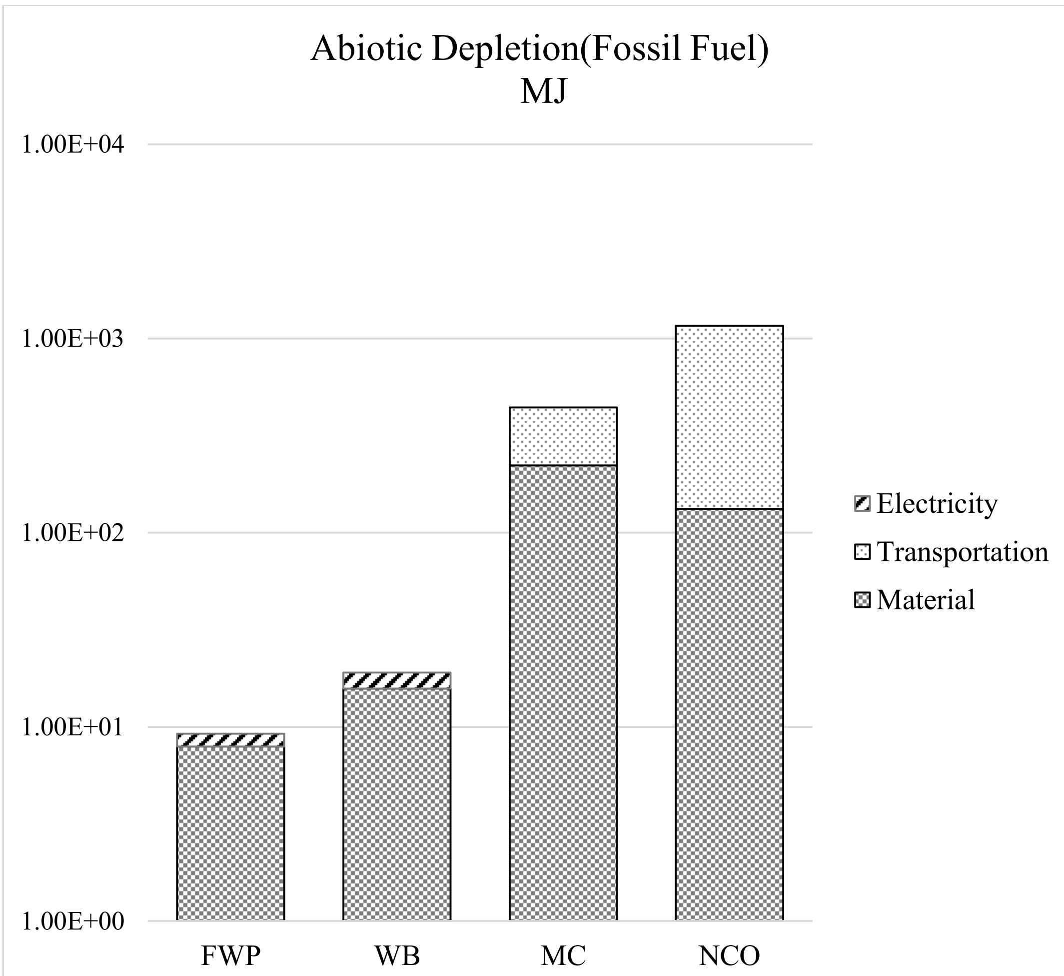

Figure 34: Abiotic Depletion (Fossil Fuels)

4.2.3 Global Warming Potential (GWP)

The global warming potential of four oil and gas repair processes is measured in terms of kg CO_2 /kg emission and plotted on log scale as shown in Figure 35 which depicts the contribution of materials, electricity and transportation in GWP.

Composite overwrap has highest impact on GWP as compared to other repair processes because of transportation whereas, fillet welded patch has the least. Mechanical clamp has the second highest impact value in which both material and transportation have almost equal contribution. Weld buildup and fillet welded patch have small impact on GWP. Overall, pipe wrap and mechanical clamp are mainly responsible for global warming potential.

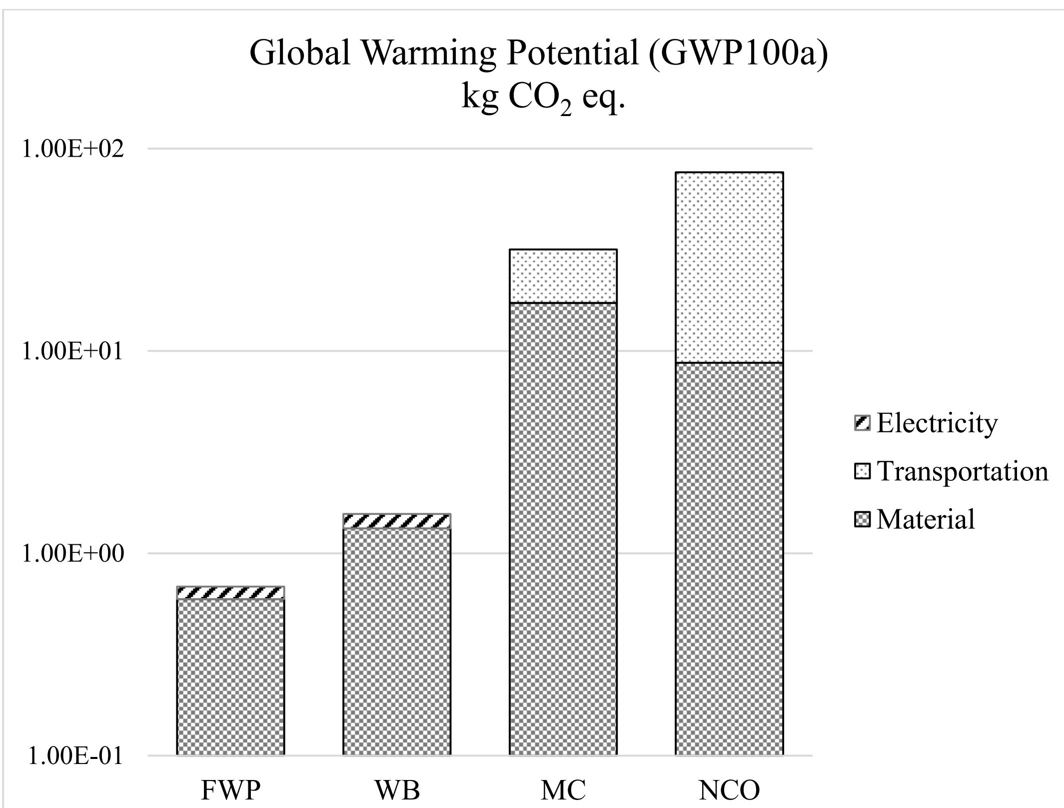

Figure 35: Global Warming Potential

4.2.4 Ozone Depletion Potential (ODP)

This impact category is concerned with emissions causing the depletion of stratospheric ozone layer. As a result of this, an enormous fraction of ultraviolet rays reaches the earth surface causing the detrimental effects upon health and ecosystem. ODP is measured in term of kg CFC-11/kg emission and plotted in log scale as shown in Figure 36 which shows the contribution of materials, electricity and transportation in ODP.

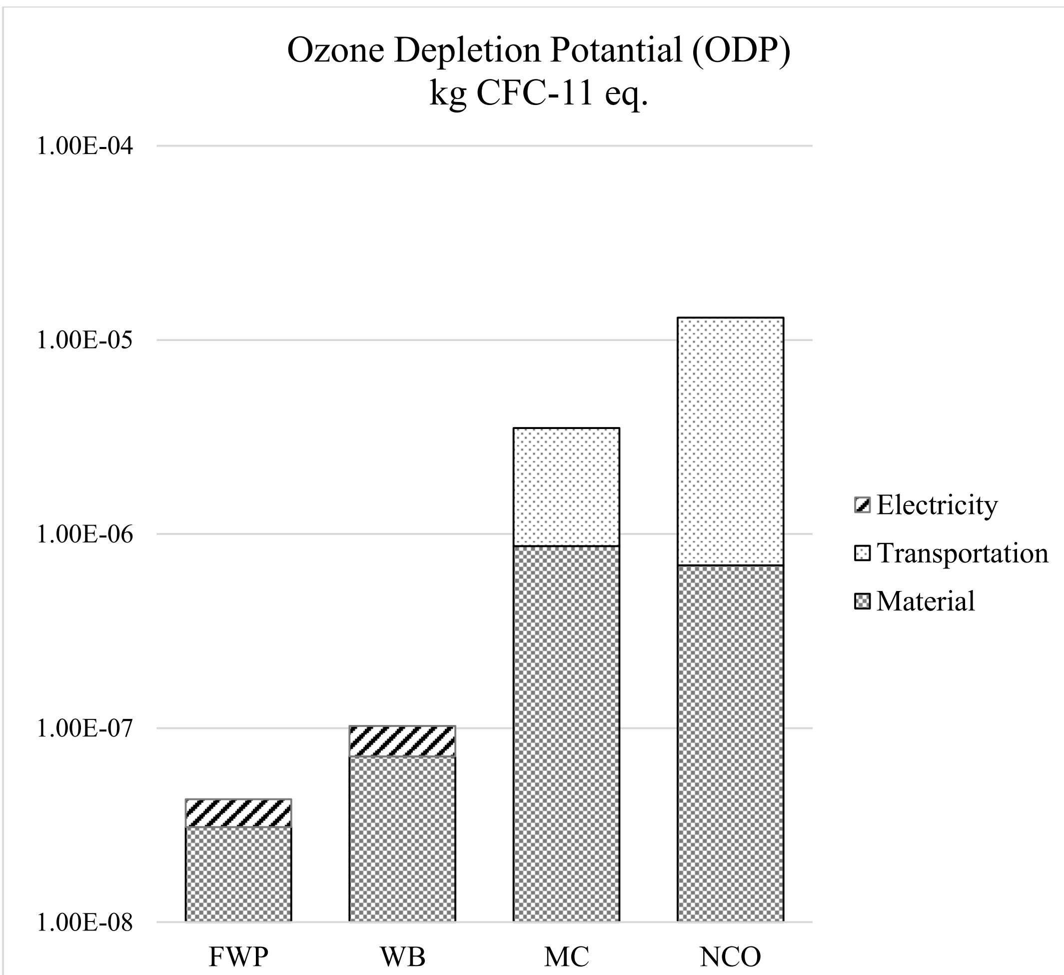

Figure 36: Ozone Depletion Potential

Composite overwrap repair process has highest ODP as compared to other repair processes whereas, fillet welded patch has the least. Within mechanical clamp and composite overwrap repair technique, transportation is most contributing in ODP. However, materials also have significant contribution. In the case of weld buildup and fillet welded patch repair techniques; materials have more contribution than electricity. However, overall impact is very low as compared to mechanical clamp and composite overwrap.

4.2.5 Human Toxicity Potential (HTP)

It is related to effects of toxic substances on human environment. HTP is measured in 1,4-dichlorobenzene equivalents/kg emission and plotted on log scale as shown in Figure 37 which shows the contribution of materials, electricity and transportation in HTP.

Mechanical clamp has the highest HTP as compared to other repair processes because of materials (mainly steel) whereas, fillet welded patch has the least HTP. Composite overwrap has the second highest impact value in HTP in which transportation dominate the impact. The welding repair techniques have small contribution in HTP. Overall, materials used in mechanical clamp is mainly responsible for HTP.

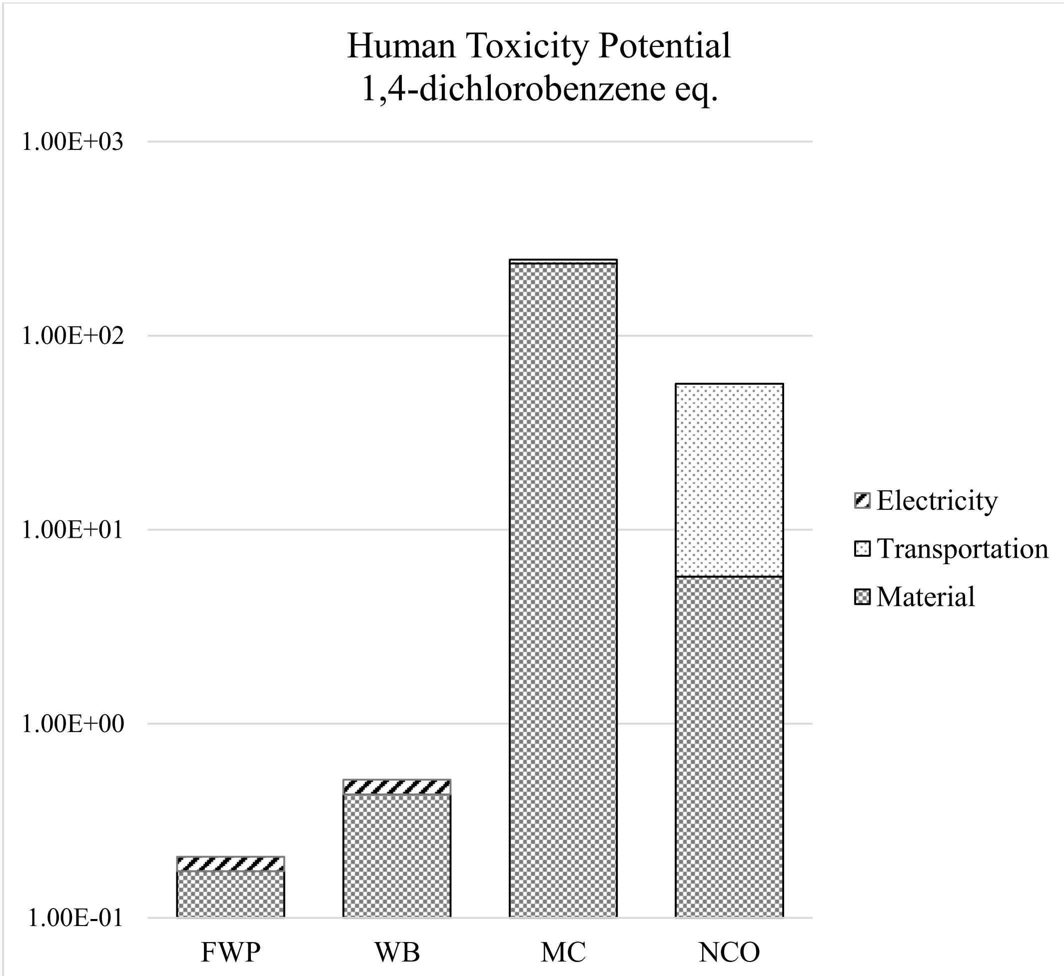

Figure 37: Human Toxicity Potential

4.2.6 Fresh Water Aquatic Ecotoxicity

This impact category is related to fresh water ecosystem, as result of emission of noxious substances to soil, water and air. Fresh water aquatic ecotoxicity potential is measured in 1, 4-dichlorobenzene equivalents/kg emission and plotted on log scale as shown in Figure 38 which depicts the contribution of repair processes in fresh water aquatic ecotoxicity potential.

From Figure 38, it is clear that mechanical clamp has the highest impact on fresh water aquatic ecotoxicity potential because of materials as compared to other repair processes whereas, fillet welded patch has the least. Composite overwrap has the second highest impact value in which materials and transportation both have almost equal contribution. Welding repair techniques also have small impact mainly because of materials used in these processes. Overall, mechanical clamp mainly causing harmful effects on fresh water ecosystem.

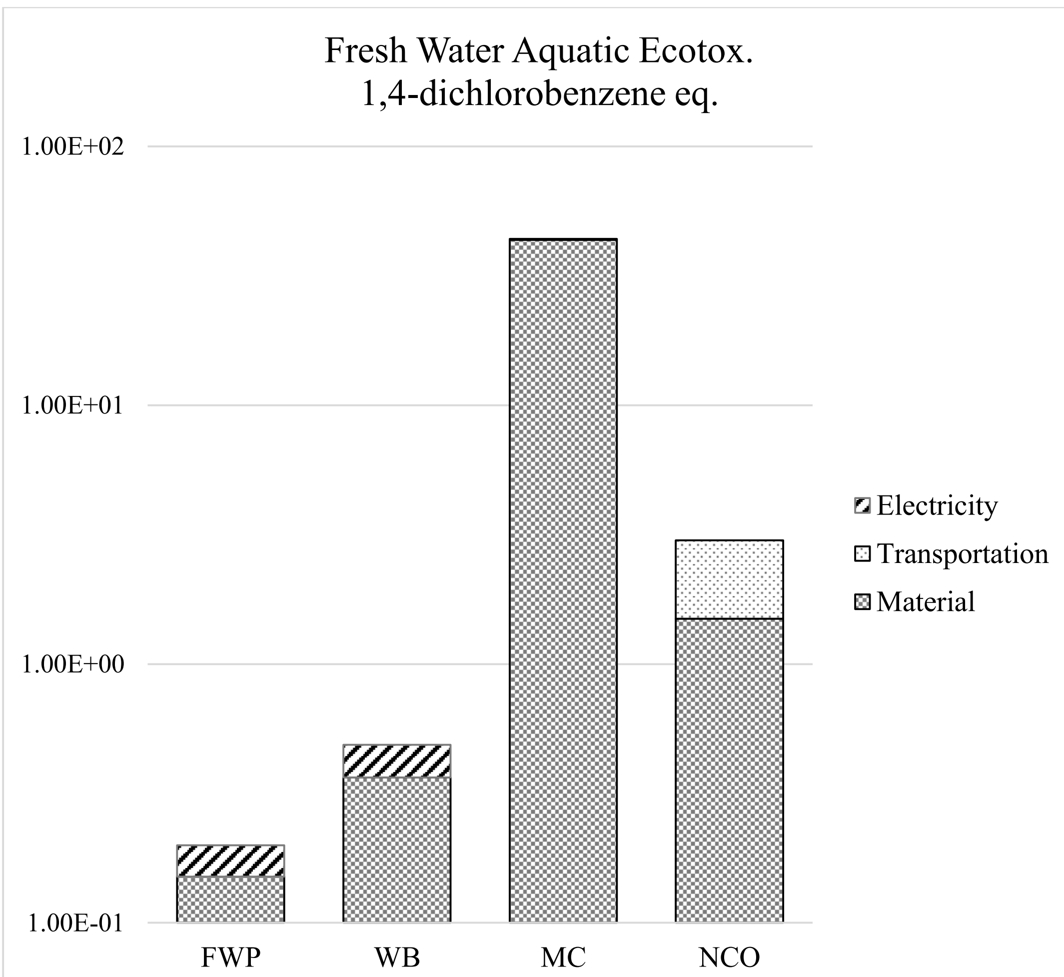

Figure 38: Fresh Water Aquatic Ecotoxicity

4.2.7 Marine Aquatic Ecotoxicity

Marine ecotoxicity is concerned with the effect of toxic substances on marine ecosystem. It is measured in 1, 4-dichlorobenzene equivalents/kg emission and plotted in log scale as shown in Figure 39 which presents the contribution of materials, electricity and transportation in marine aquatic ecotoxicity.

Mechanical clamp has the highest impact on marine aquatic ecotoxicity potential as compared to other processes whereas, fillet welded patch has the least. Within all repair processes, materials are most contributing in marine ecotoxicity potential. However, transportation of composite overwrap also has significant impact. Remaining inputs have small contribution in marine aquatic ecotoxicity potential.

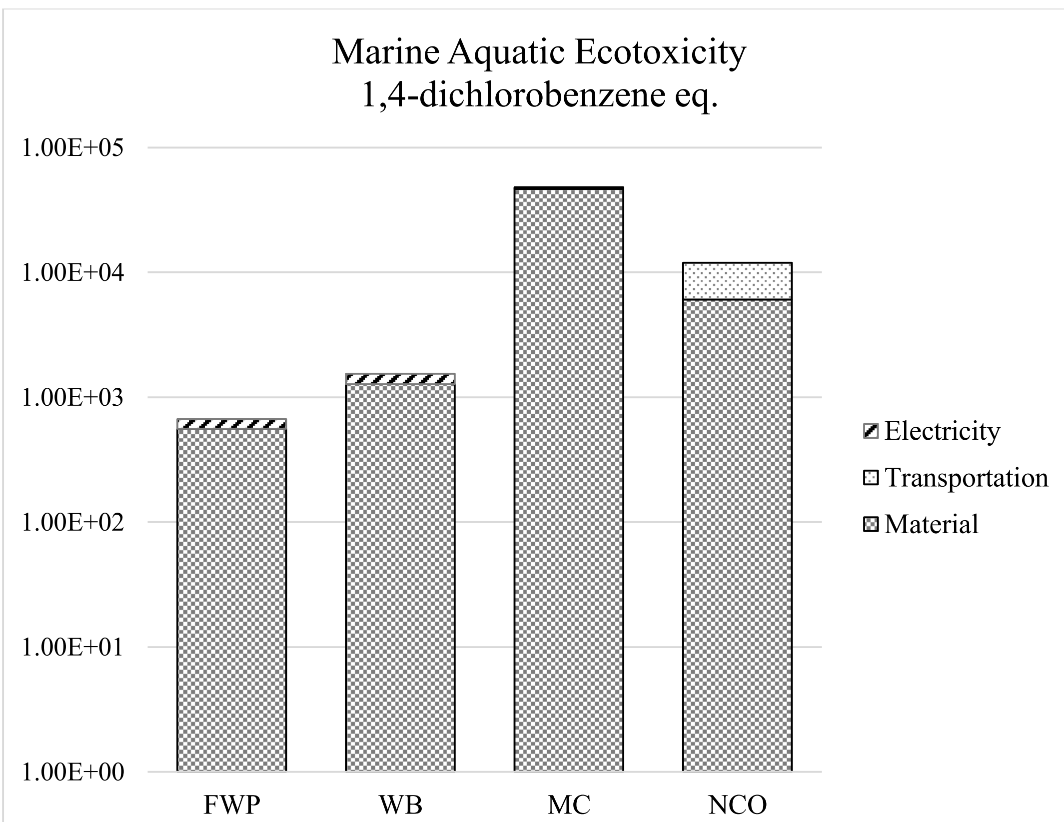

Figure 39: Marine Aquatic Ecotoxicity

4.2.8 Terrestrial Ecotoxicity

Terrestrial ecotoxicity is concerned with effect of toxic substances on terrestrial system. It is also measured in 1, 4-dichlorobenzene equivalents/kg emission and plotted on log scale as shown in Figure 40 which shows the contribution of materials, electricity and transportation in terrestrial ecotoxicity.

Mechanical clamp has highest impact on terrestrial ecotoxicity as compared to other repair processes whereas, fillet welded patch has the least impact. Materials have dominant impact within all repair processes. However, transportation of composite overwrap also has significant impact value. Other remaining inputs have small contribution in terrestrial ecotoxicity.

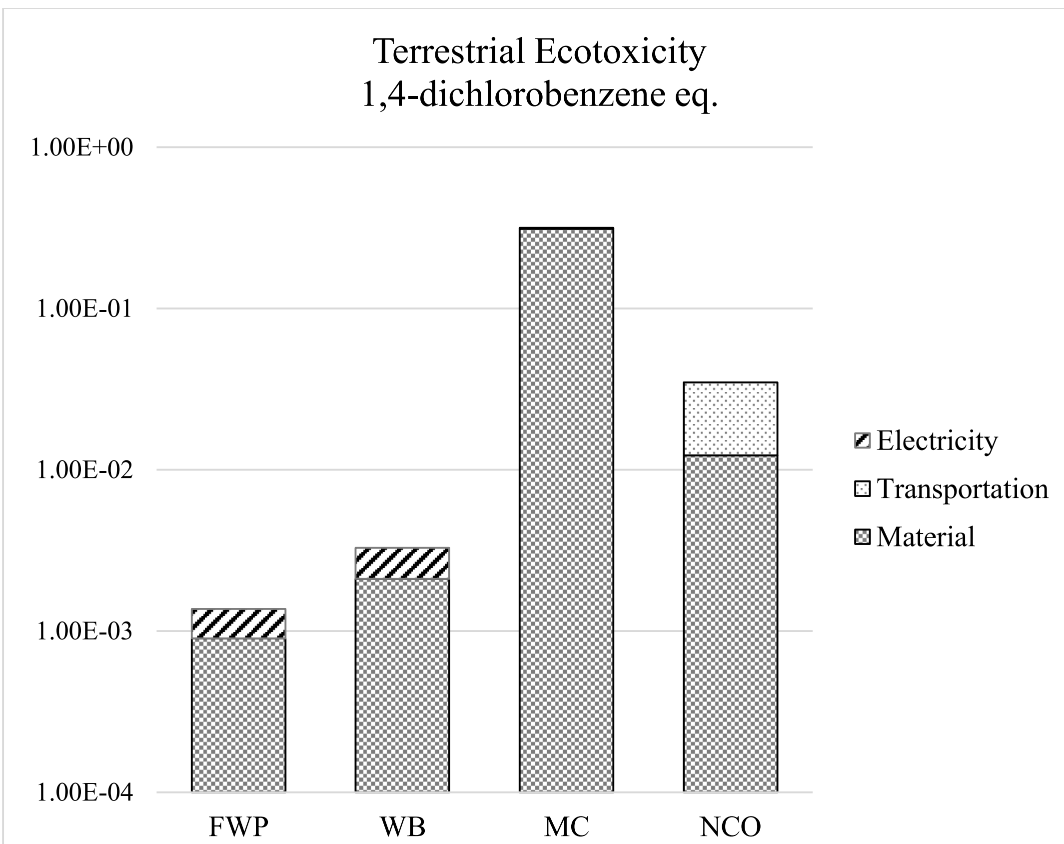

Figure 40: Terrestrial Ecotoxicity

4.2.9 Photochemical Oxidation

This category accounts for emissions, cause the formation of reactive substances in air, which is harmful to human health and ecosystem. This category is expressed in kg ethylene equivalents/kg emission and plotted on log scale as shown in Figure 41 which shows the contribution of materials, electricity and transportation in photochemical oxidation potential.

From Figure 41, it is clear that composite overwrap has highest impact on photochemical oxidation potential as compare to other repair processes, whereas fillet welded patch has the least. Within all repair processes, materials are most contributing in photochemical oxidation potential. However, transportation of composite overwrap and mechanical clamp also has significant contribution. Weld buildup and fillet welded patch have small impact on photochemical oxidation potential.

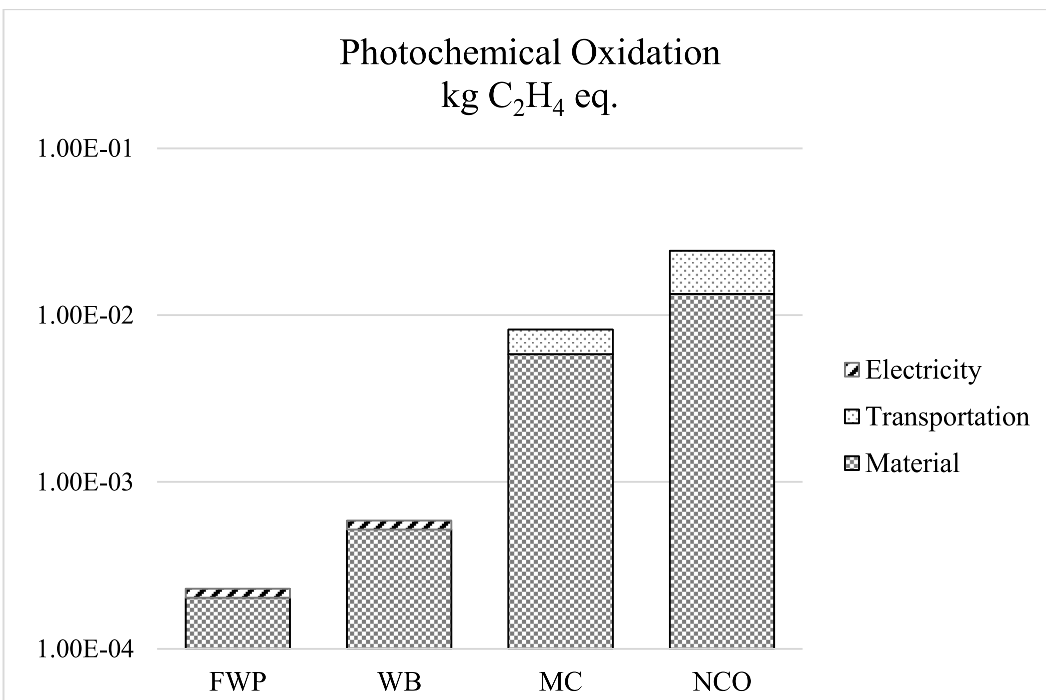

Figure 41: Photochemical Oxidation

4.2.10 Acidification Potential (AP)

This category represents effect of substances causing the acidity of soil and water. It is expressed in SO_2 equivalents/kg emission and plotted on log scale as shown in Figure 42 which depicts the contribution of materials, electricity and transportation in AP.

Composite overwrap has highest impact on AP as compared to other repair processes because of transportation whereas, fillet welded patch has the least. Mechanical clamp has second highest impact value in which material is most contributing in AP. Within welding repair technique, weld buildup has high impact than fillet welded patch. However, overall impact is very small impact as compared to mechanical clamp and composite overwrap.

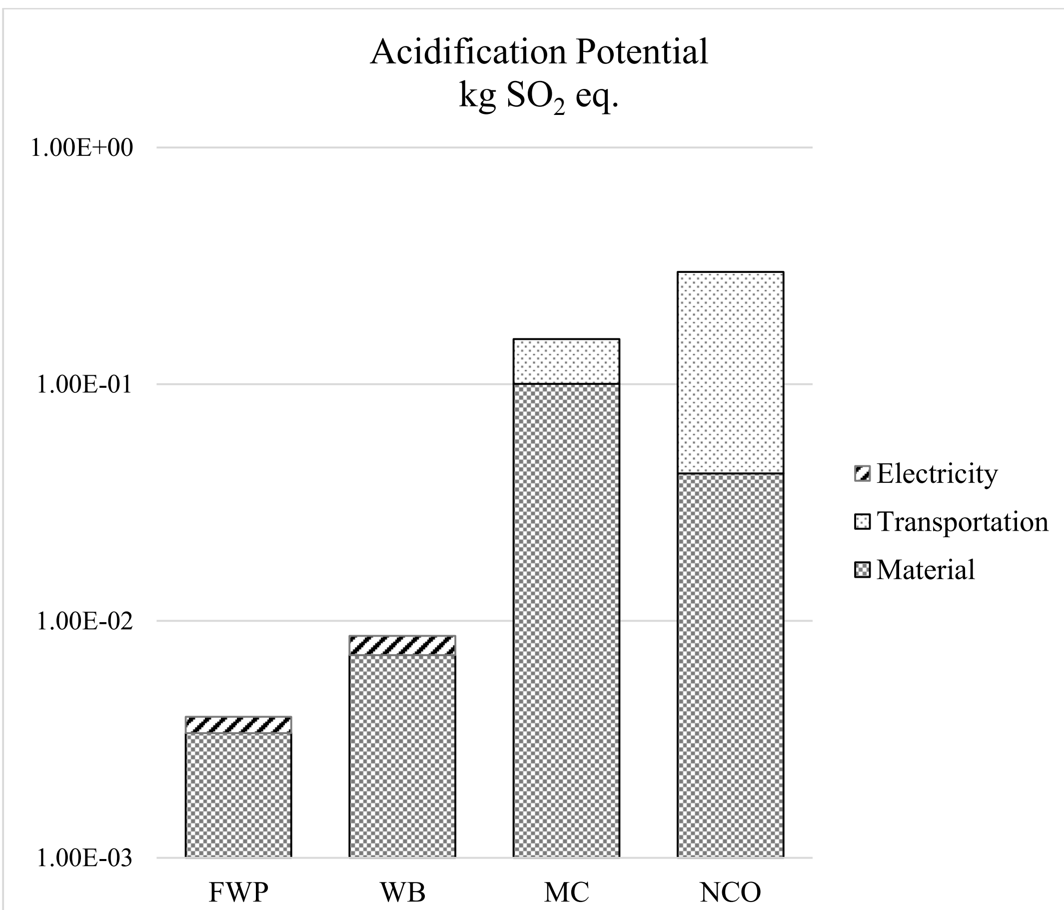

Figure 42: Acidification Potential

4.2.11 Eutrophication Potential (EP)

This category measure the effect caused by emission of micro nutrients to air, water and soil. It is expressed as kg PO_4 equivalents per kg emission and plotted on log scale as shown in Figure 43 which shows the contribution of materials, electricity and transportation in EP.

From Figure 43, it is clear that composite overwrap has highest impact on EP because of transportation as compared to other repair processes, whereas, fillet welded patch has the least. Mechanical clamp has second highest impact value in which materials are most contributing. Within welding repair technique, weld buildup has high impact than fillet welded patch, however, impact is very small as compare to mechanical clamp and composite overwrap.

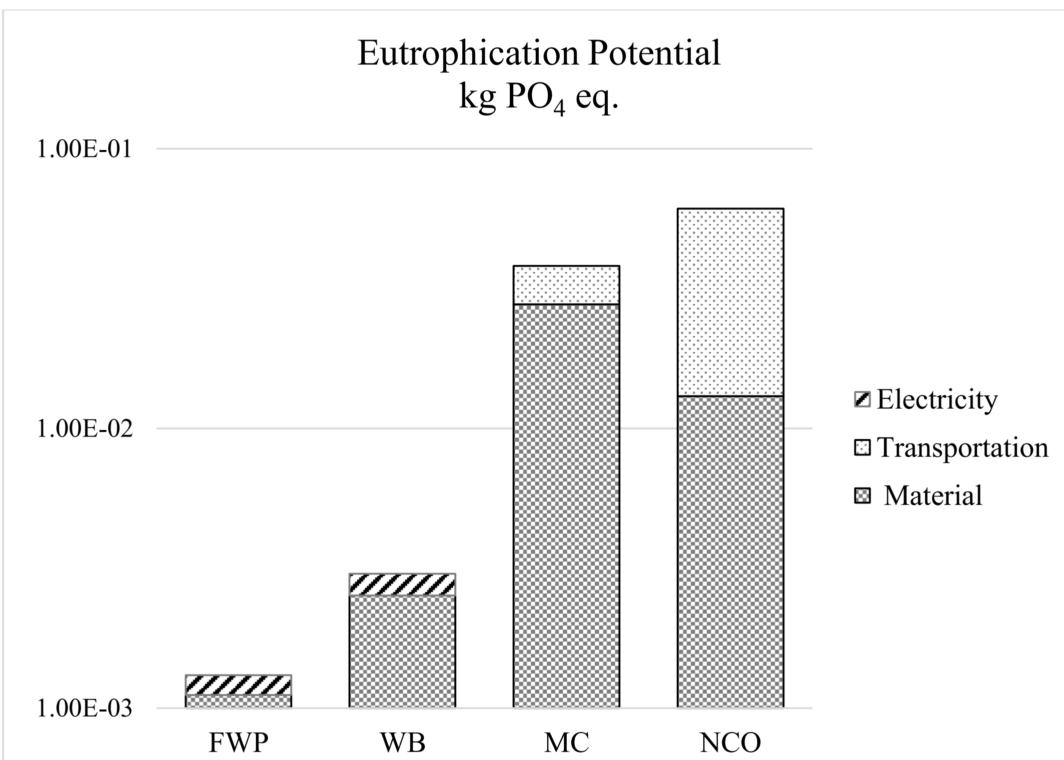

Figure 43: Eutrophication Potential

4.3 Sensitivity Analysis

According to ISO 14044 [46], sensitivity analysis is a procedure which estimates the effect of changes made regarding data used in LCA analyses. As, it is clear from Life Cycle Impact Assessment (LCIA) results that transportation used for mechanical clamp and composite overwrap, and steel used in mechanical clamp have largest environmental impacts. Also, glass fiber used in composite overwrap has significant environmental impact. Therefore, along with transportation and steel inputs, effect of change of glass fiber is investigated using sensitivity analysis in order to observe the change in environmental impacts of repair techniques.

In order to perform sensitivity analysis, three scenarios are compared with base scenario as mentioned below:

- In first scenario, it is assumed that both composite overwrap and mechanical clamp are manufactured locally. Therefore, local transport is used.
- Whereas, in second case, carbon steel is used instead of stainless steel to manufacture mechanical clamp. This assumption is valid according to ASME PCC-2. Stainless steel is used for clamp because it is highly corrosion resistant material according to clamp manufacturer.
- In the third scenario, glass fiber consumption is reduced by 10 % to observe the variation in the environmental impact of composite overwrap.

These three scenarios are compared with base scenario by varying only one data each time to underline the outcome and results for sensitivity analysis are shown below:

The results of sensitivity analysis for abiotic depletion potential are shown in Figure 44 on log scale. It is clear that abiotic depletion potential (ADP) is high due to stainless steel used in mechanical clamp (see scenario two in Figure 44) because by changing the material from stainless steel to carbon steel, ADP has reduced by 98%. Whereas, in scenario one, ADP due to mechanical clamp didn't change significantly but decreased by 21% in case of composite overwrap. However, due to 10% reduction in glass fiber consumption ADP is slightly changed and decreased by 7.39 %.

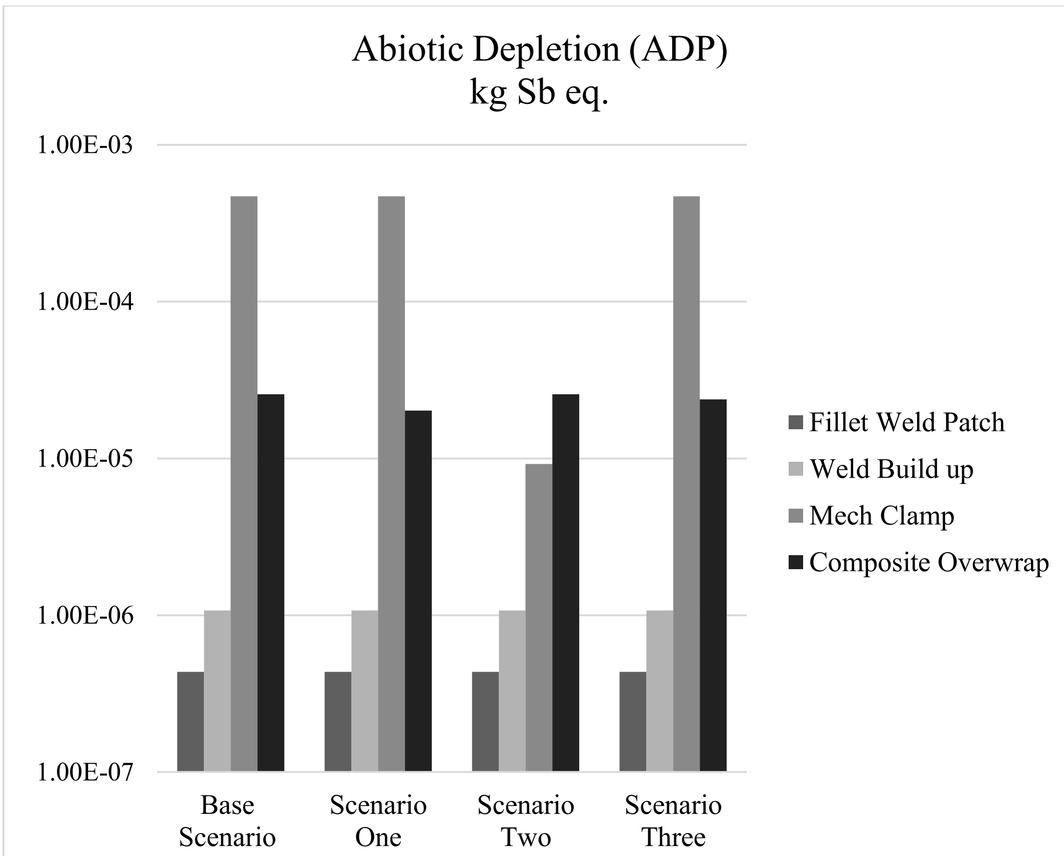

Figure 44: Sensitivity Analysis Result: Abiotic Depletion

Sensitivity analysis results for abiotic depletion (fossil fuel) shows that transportation is mainly responsible for this impact (see Figure 45). Because in scenario one, impact has reduced significantly i.e. 49% in clamp and 88% in overwrap. However, change the steel material has comparatively small effect on this impact category i.e. reduced by 21%. Whereas, 10% reduction in glass fiber consumption has very small effect on ABD (fossil fuel) i.e. -0.917%. Negative sign shows that impact is reduced.

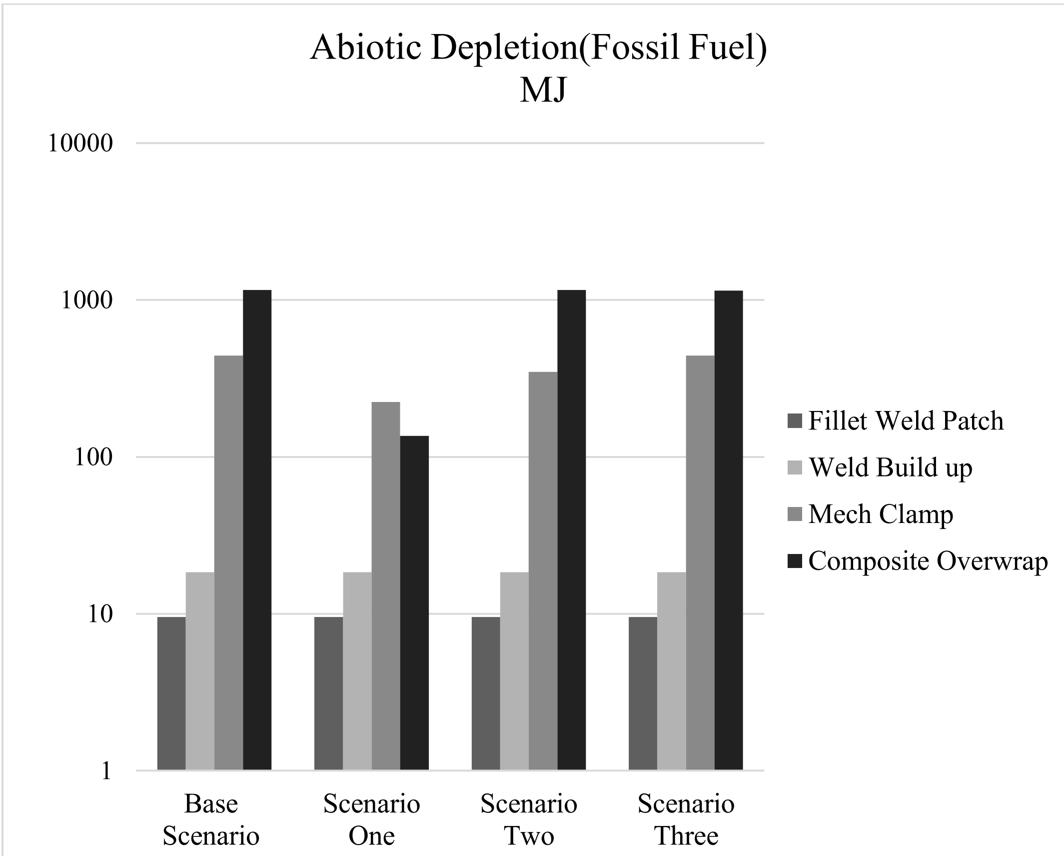

Figure 45: Sensitivity Analysis Result: Abiotic Depletion (fossil fuel)

The sensitivity analysis results for GWP is clearly depicting that transportation is the most contributing input. (see Figure 46, scenario one), i.e. the variation in GWP is -45% in case of clamp and -88% in composite overwrap. Where, negative sign shows the reduction in environmental impact. Altering the steel material has small effect as compared to transportation i.e. -22%. However, change in glass fiber consumption didn't change the GWP significantly. i.e. reduction in GWP is -0.97%.

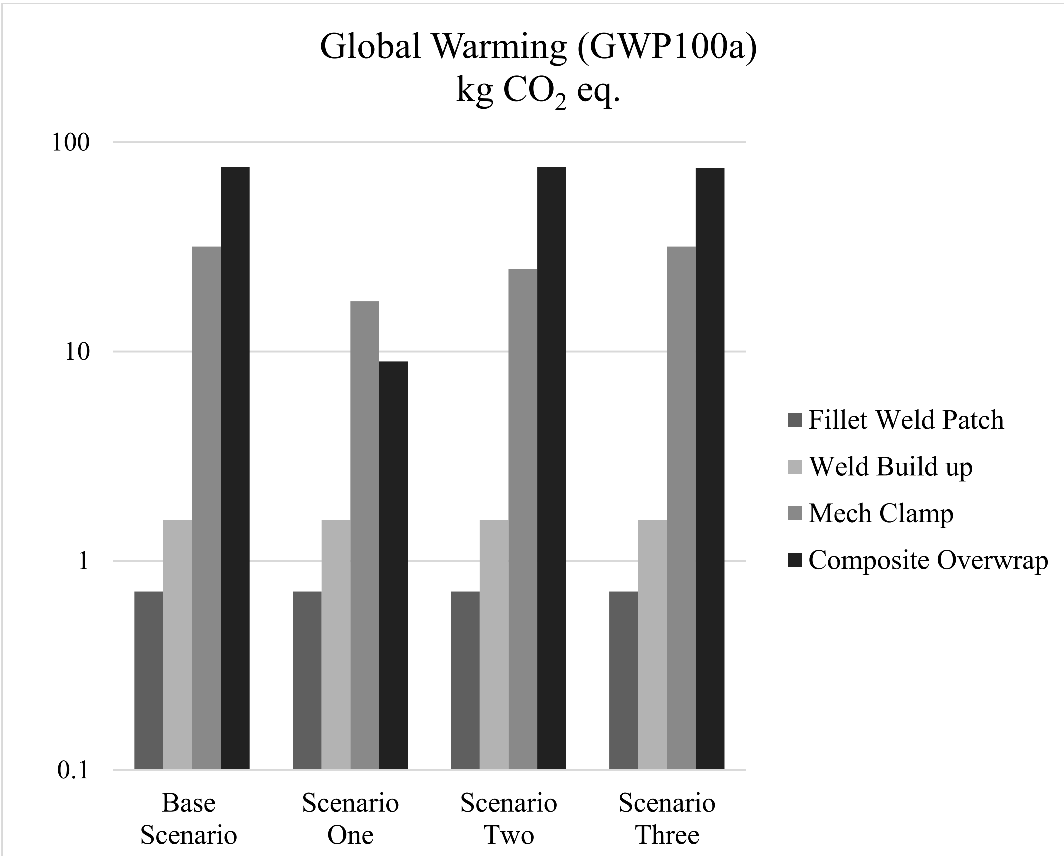

Figure 46: Sensitivity Analysis Result: Global Warming Potential

Sensitivity analysis results of ODP in Figure 47 show that transportation is responsible for such high ozone depletion potential (see scenario one). i.e. ODP has reduced by 74.8% in case of clamp and 94% in composite overwrap. Variation in steel material has decreased the ODP by 15% (see scenario two). Change in glass fiber consumption didn't make any noticeable change in ODP i.e. impact is reduced by 0.001%.

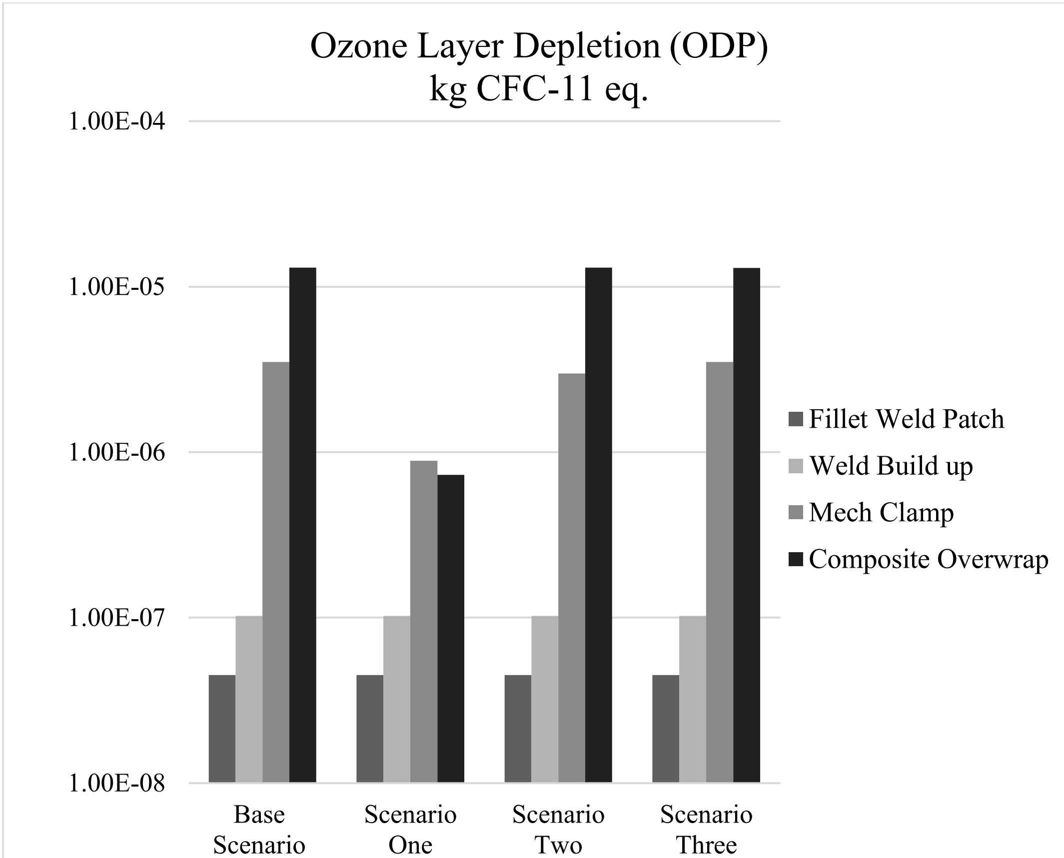

Figure 47: Sensitivity Analysis Result: Ozone Depletion Potential

Sensitivity analysis result of HTP is shown in Figure 48 which depicts that transportation and stainless steel both are most contributing inputs. In scenario one, HTP has reduced by 4.4% in case of clamp and 89% in composite overwrap. Whereas, in second scenario, HTP has reduced by 94%. 10% reduction in glass fiber consumption has change the HTP just by -1.09%. Scenario three results suggest that glass fiber consumption didn't have any significant effect on HTP.

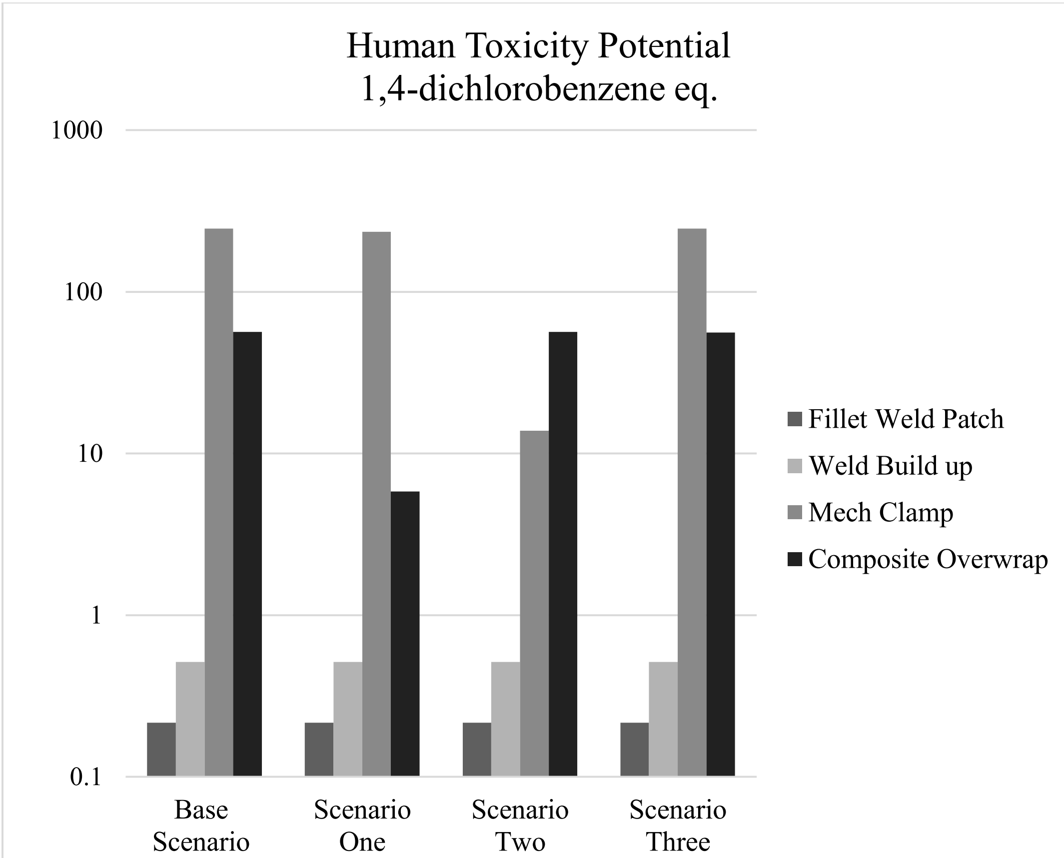

Figure 48: Sensitivity Analysis Result: Human Toxicity Potential

Sensitivity analysis results for fresh water aquatic ecotoxicity show that stainless steel is mainly responsible for this potential (see Figure 49, scenario two). i.e. impact is reduced by 94%. However, effects of transportation are small i.e. impact is reduced by 0.6% in case of clamp and 48% in composite overwrap. 10% reduction in glass fiber consumption (scenario three) has decreased the fresh water ecotoxicity potential by 5 % which is small variation as compared to transportation (scenario one) and stainless steel material (scenario two).

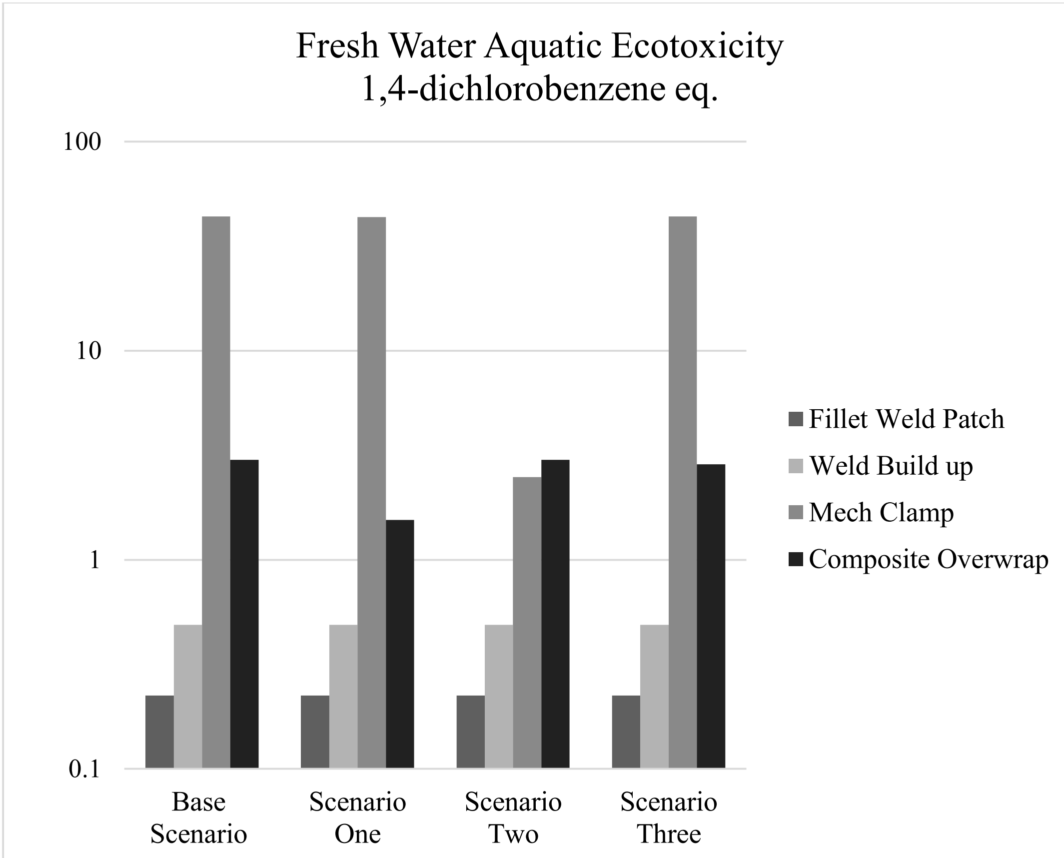

Figure 49: Sensitivity Analysis Result: Fresh Water Aquatic Ecotoxicity

The sensitivity analysis results for marine ecotoxicity potential (MEP) shows that materials are most contributing input (see Figure 50). However, transportation of composite overwrap also has significant impact i.e. MEP has decreased by 47% in scenario one and 86% in scenario two. Therefore, stainless steel is most responsible for increasing MEP. Decreasing the glass fiber consumption by 10% also reduced the MEP by 5.39%. Overall, result shows that MEP can be minimized by reducing the consumption of resources.

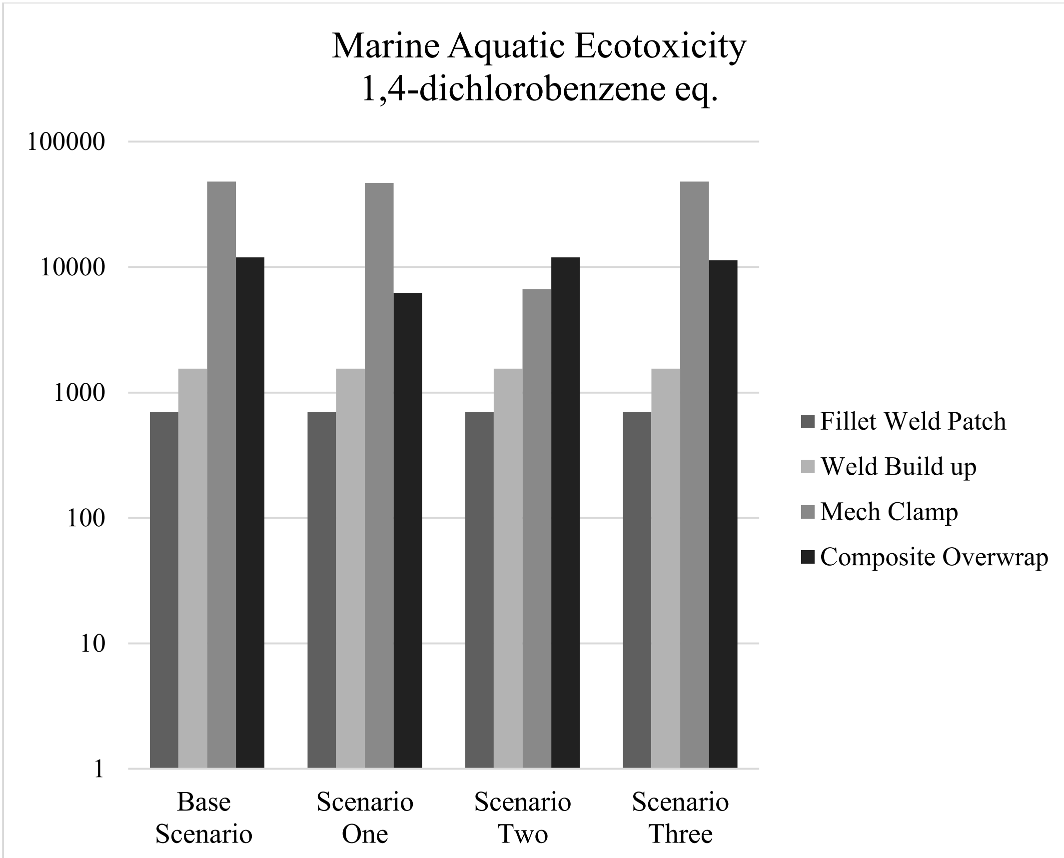

Figure 50: Sensitivity Analysis Result: Marine Aquatic Ecotoxicity

As similar to previous ecotoxicity potentials, terrestrial ecotoxicity has also the same trend (see Figure 51) i.e. replacement of stainless steel has reduced the impact significantly i.e. 95%. However, transportation of composite overwrap has also reduced the impact by 64%. Whereas, reduction in glass fiber consumption has small effect on terrestrial ecotoxicity results i.e. impact is reduced by only 2.91%.

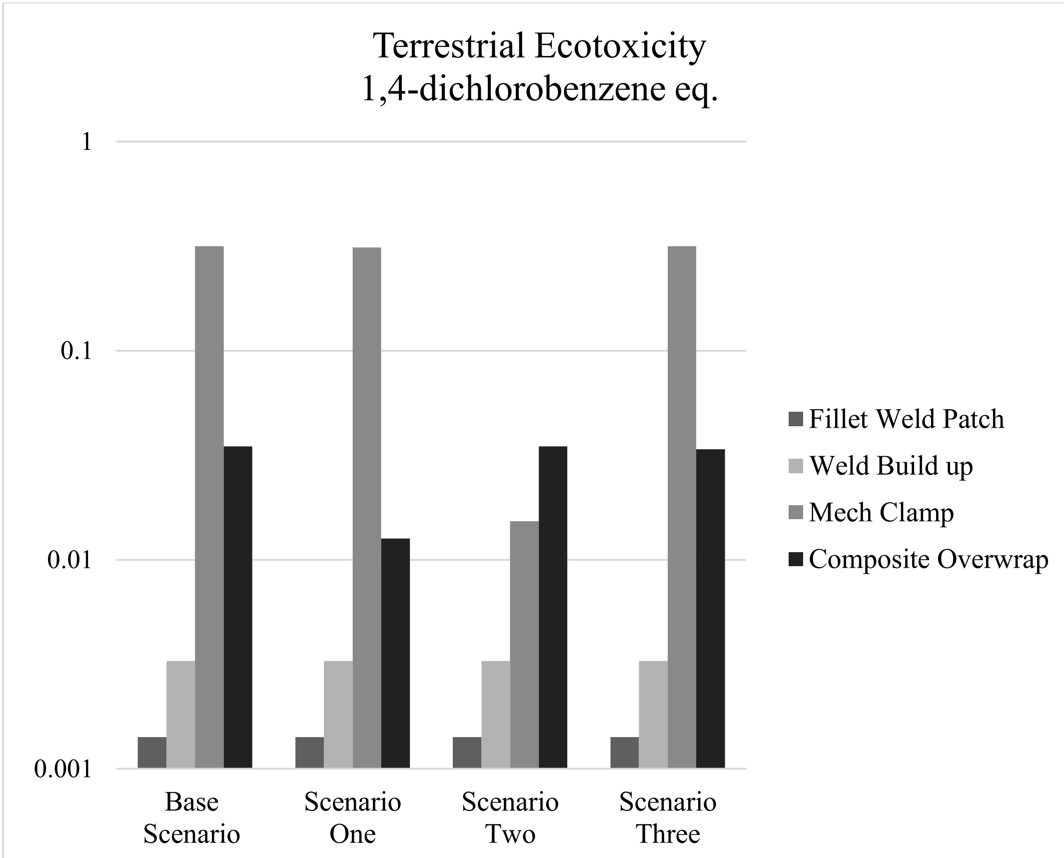

Figure 51: Sensitivity Analysis Result: Terrestrial Ecotoxicity

Photochemical oxidation potential has not been effectively changed with the variation of inputs (see Figure 52) and also there is no change in trend. In scenario one, impact has decreased by 28% in case of clamp and 44% in composite overwrap. Whereas, in scenario two, impact has reduced by 13%. Reduction in glass fiber composition has decreased the impact by 5.32% which is very small as compared to transportation (scenario one) and stainless steel (scenario two).

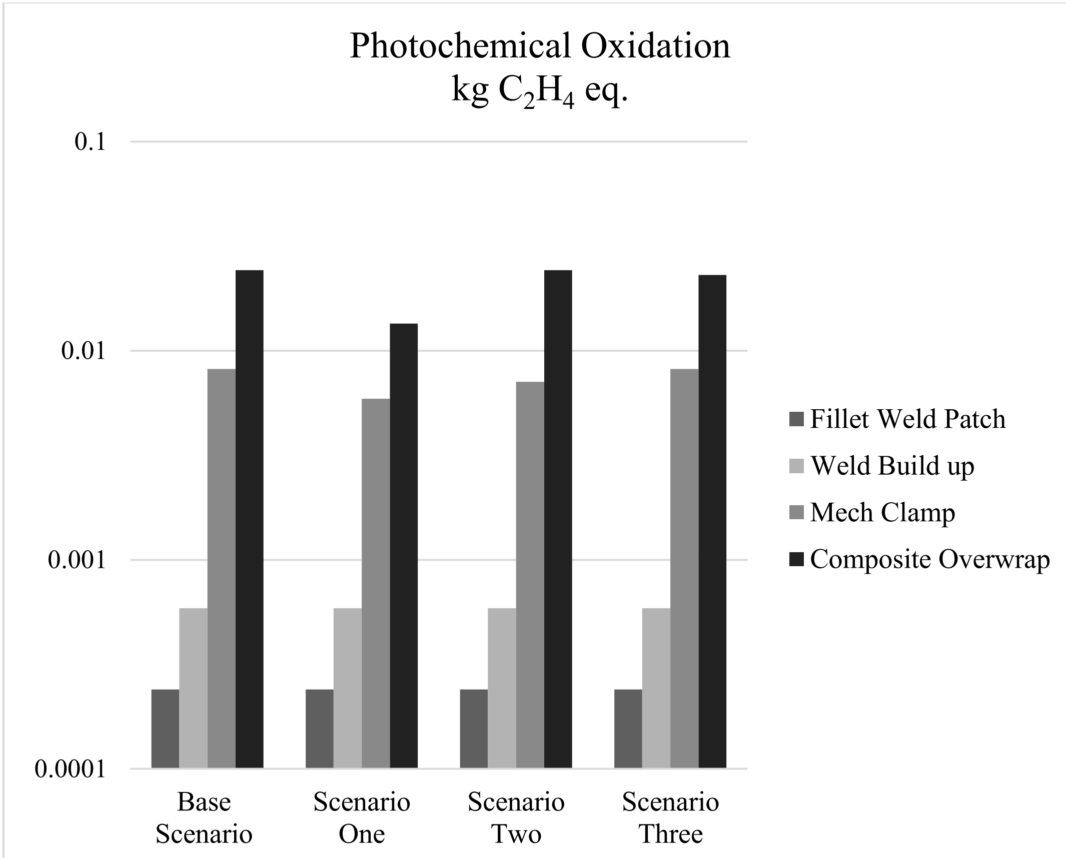

Figure 52: Sensitivity Analysis Result: Photochemical Oxidation

Sensitivity analysis results for AP show that transportation (scenario one) has large impact on AP. Impact is reduced by 35% in case of clamp and 85% in composite overwrap as compared to base scenario. However, variation of steel material decreased the impact by 40% (see Figure 53). Change in glass fiber consumption (scenario three) reduced the impact by only 1%. Which is comparatively very small as compared to first two cases.

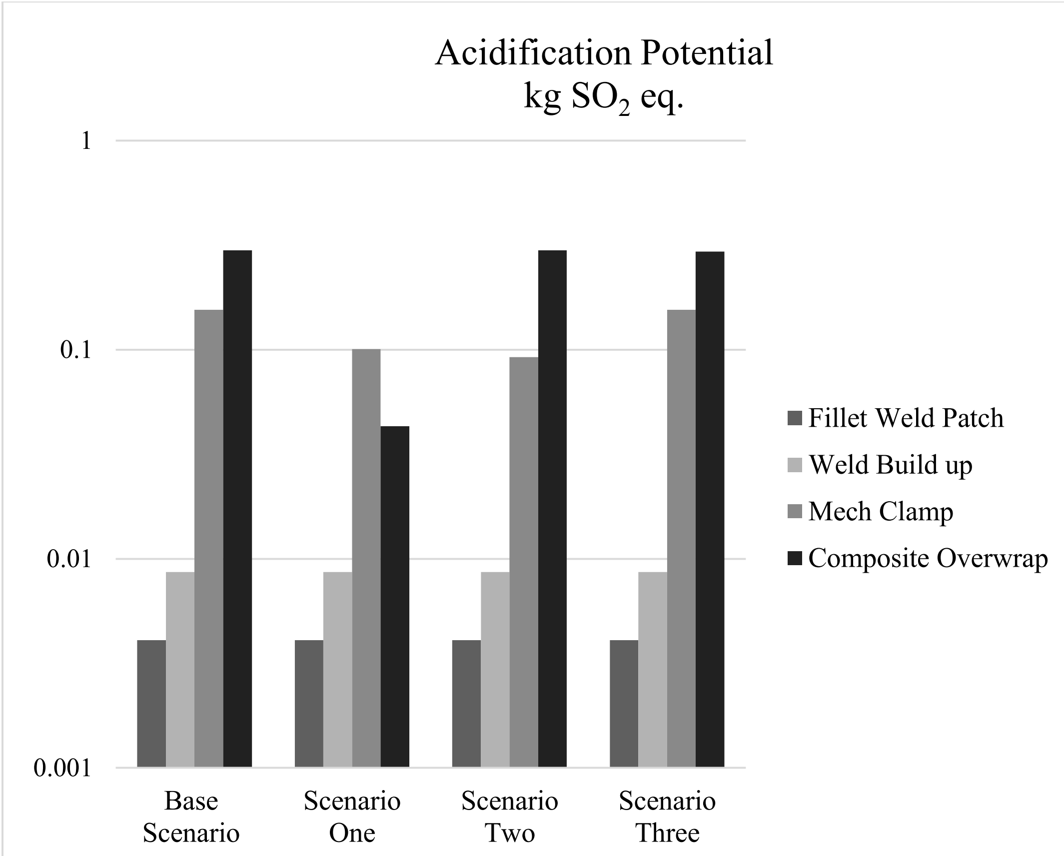

Figure 53: Sensitivity Analysis Result: Acidification Potential

As similar to AP, EP also has large reduction in impact value i.e. 27% in case of clamp and 78% in composite overwrap as compared to base scenario because of transportation (see Figure 54, scenario one). However, change of steel material (scenario two) also has noticeable effect i.e. impact is reduced by 42% (compared with base scenario). In case of third scenario, effect is very small as compared to other cases, the impact value is decreased by only 2%.

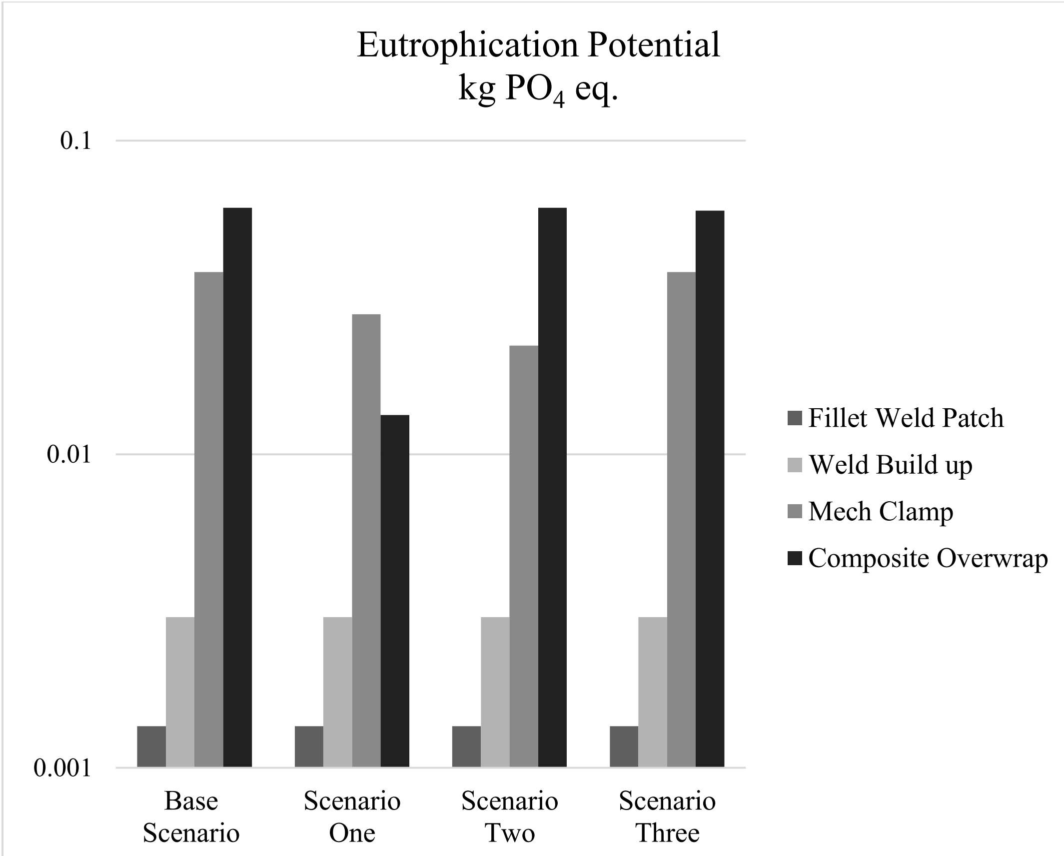

Figure 54: Sensitivity Analysis Result: Eutrophication Potential

The summary of sensitivity analysis results show that environmental impacts are considerably reduced in all cases. However, the variation in impact value was very small in scenario three as compared to scenario one and two. Generally, it is found that change in transportation used in mechanical clamp and composite overwrap process and stainless steel material used in mechanical clamp considerably reduced the environmental impact. specifically, abiotic depletion (fossil fuel), GWP, ODP, photochemical oxidation, AP and EP are greatly reduced by considering the composite overwrap and mechanical clamp as local product (scenario one). However, variation in steel material does not have noticeable effect in above impact categories.

The use of carbon steel material instead of stainless steel (scenario two) in mechanical clamp has significantly reduced the abiotic depletion potential, human toxicity potential, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity and terrestrial ecotoxicity however, all other impacts are slightly reduced. Reduction in consumption of glass fiber material (scenario three) used in composite overwrap has small effect on environmental impacts as compared to base scenario however, the effect is noticeable in abiotic depletion potential and ecotoxicity potential.

4.4 Discussion

Amongst the investigated processes for repairing the local wall thinning defect due to external corrosion, life cycle impact assessment and sensitivity analysis results show that, fillet welded patch is the most environmental friendly repair solution and best option to select considering the contributed environmental impact. Because it requires welding with least number of passes on the periphery of steel plates which reduces consumption of filler metal, shielding gas and electricity and overall weld volume as compared to weld build up. Main reason for less environmental impact is the design requirement of this repair process and less amount of materials used. There is no such material in this techniques which is causing the harmful effect on environment as compared to other repair techniques. Due to design of fillet welded patch, electricity consumption is also minimized. However, in case of weld build up, it is comparatively high due to large process time.

Weld buildup repair process also has significantly low environmental impact as compared to composite overwrap and mechanical clamp. However, it is more in comparison to fillet welded patch in all impact categories. The reason behind it is that filler metal, shielding gas and electricity consumptions are more in weld buildup.

Contrary to fillet welded patch, composite overwrap and mechanical clamp lead to highest environmental impact. First reason is that resources used in these repair processes are much higher in quantity as compared to fillet welded patch and weld build up. Secondly, these resources are more harmful to environment like stainless used in mechanical clamp is the cause of major environmental problem related to ecotoxicity. Mechanical clamp dominates in impact categories related to human, fresh water, marine and terrestrial ecotoxicity. This is mainly because of stainless steel, as investigated through sensitivity analysis. By changing the steel material; impacts related to these categories have reduced significantly. The reason is that, stainless steel contains alloying element such as chromium etc. whereas, carbon steel is simple steel having small percentage of carbon. On the other hand, composite overwrap dominates in impact categories related to climate change and GWP. This is due to emissions of aircraft used for transportation as it has also been proved through sensitivity analysis. Aircraft engine emits the particulate matter, heat and gasses which results in climate change and GWP problems [43].

Hence, in order to improve the environmental impacts of composite overwrap and mechanical clamp, the assumptions made in sensitivity analysis should be considered. As it has been observed, that change of material has large effect on environmental impact. Therefore, some other materials should also be investigated which are good in both perspectives i.e. environmental friendly as well as corrosion resistant.

Hence, the LCA results represent clear environmental preference and it can be concluded that fillet welded patch is the best environmental friendly repair solution for repairing small local wall thinning defect due to external corrosion. but limitations of study need to be acknowledged. The results of this study are valid for the defect type and size, mentioned in Chapter 3. Because due to the change in defect size; design and dimensions of repair processes might be changed according to ASME PCC-2 standard. Secondly, there is a possibility that some other repair processes need to be preferred over current processes, as fillet welded patch and weld build up are normally used for small defect sizes and are not suitable for large defects [15]. However, composite overwrap has broader scope, it can be used for any defect type and size [31]. Furthermore, testing procedure of repair techniques has not been included in the scope of study which may have some environmental impact. The overall conclusions and future work are discussed in the following chapter.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

This study presented the LCA of four oil and gas pipe repair processes: Weld buildup, fillet welded patch, mechanical clamp and composite overwrap. Environmental impacts of these processes are compared quantitatively and following conclusions can be made on the basis of LCA and sensitivity results discussed in Chapter 4:

1. Environment impact assessment was made by CML method which include abiotic depletion, abiotic depletion (fossil fuel), global warming potential, ozone depletion potential, human toxicity, fresh water aquatic ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification potential, and eutrophication potential. From the results, it is clear that composite overwrap and mechanical clamp have highest environmental impact whereas fillet welded patch has the least.
2. Within welding repair techniques, weld buildup has high environmental impact as compared to fillet welded patch in all impact categories. However, both welding repair techniques have small environmental impact as compared to other repair techniques.
3. Mechanical clamp repair technique has highest impact on abiotic depletion potential, human toxicity, fresh water aquatic ecotoxicity, marine ecotoxicity and

terrestrial ecotoxicity as compared to other repair techniques. From the sensitivity analysis results, it is clear that stainless steel is mainly responsible for higher impact.

4. Composite overwrap repair process has highest environmental impact on abiotic depletion potential (fossil fuel), global warming potential, ozone depletion potential, photochemical oxidation, acidification and eutrophication. The sensitivity analysis results show that transportation is the most contributing factor. In addition, materials used in composite overwrap also have significant impact.
5. Composite overwrap is a modern repair technique, and has broad scope in industrial repair applications. LCA results showed that it is a less environmental friendly repair solution.
6. Sensitivity analysis results show that transportation of composite overwrap and mechanical clamp is most contributing factor. Therefore, these processes can be made environmental friendly if these products are manufactured locally.
7. It is also revealed from sensitivity analysis, that stainless steel used in mechanical clamp technique is one of the causes of high impact. Therefore, such material should be selected that is both corrosion resistant and environment friendly.

The component material of composite overwrap repair process i.e. fiber, resins and adhesives are petroleum based products and has a high environmental impact [27] on earth's ecosystem. Therefore, the process should be modified to reduce the environmental impact because it has large industrial applications worldwide. Fillet welded patch provided most environment friendly repair solution as compared to weld build up, mechanical clamp and composite overwrap, however it is suitable only for repairing small defects. It involves welding which may require skilled staff and shutdown [44]. Moreover, the handling of welding machine and its mobility is also a critical task. Whereas, composite overwrap does not require skilled people and its installation is easy, as compare to welding repair techniques [45].

Taking into consideration the obtained LCA results, environmental investigation of industrial processes is essential for sustainable environment. In Saudi Arabia, very few studies have been performed to study the environmental impact of industrial processes. As an initiative, the present study is performed, and it may be used as a guideline to study the environmental impacts of other industrial processes.

In future, the scope of this study can be extended with the collaboration of oil and gas industry. While considering the environmental issues as a serious problem, data for live repair should be collected with the help of oil and gas companies and results can be compared with the present study. Moreover, LCA of testing procedures before and after the repair techniques should be included in a more detailed study. Compatible alternative materials needed to be investigated in order to come up with the most environmental friendly and cost effective repair solution. Additionally, these types of studies could be extended to multiple fields of industries.

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VITAE

Personal Information

Name : **FARHAN ASHRAF**
Father's Name : MUHAMMAD ASHRAF
Date of Birth : August 30, 1991
Nationality : Pakistani
Residential Address : House # 37, Block # 15, Sector B-1 Town Ship, Lahore, Pakistan
Email : f-ashraf@live.com

Educational Qualification

S.No.	Name of Institution	Degree	Passing Year	CGPA
1.	King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia	M.Sc. Mechanical Engineering	May 2016	**3.715 / 4.0**
2.	University of Engineering and Technology, Lahore, Pakistan	B.Sc. Mechanical Engineering	Sep 2013	**3.589 / 4.0**

Professional Experience

1. **Employer : Allied Engineering and Services Pvt. Ltd**

   Period : Dec 2013 - Aug 2014
   Position : Rental Sales Engineer
   Activities : After sales services for Caterpillar diesel generator

Membership

- Registered Engineer with Pakistan Engineering Council
- American Society of Mechanical Engineers

Publication

1. Ashraf, F., Shaukat, M.M., Asif, M., Pasha, S., Environmental Impact Analysis of Oil and Gas Pipe Repair Techniques Using Life Cycle Assessment (LCA), Journal of Cleaner Production, In writing