ENVIRONMENTAL AND ECONOMIC ASSESSMENT OF SUSTAINABLE MANUFACTURING PROCESSES FOR METAL PRODUCTS

by

SANDRA XIMENA LATORRE-NOGUERA

A thesis submitted to the

University of Birmingham

For the degree of

MASTER BY RESEARCH

Advanced Manufacturing Centre

School of Mechanical Engineering

University of Birmingham

August 2014

ABSTRACT

The environmental damage taking place in our world is mainly due to economic activity in the industrialised countries. Humanity's activities are contributing to the contamination of the environment which have attained global levels (e.g. the detection of trace metal and organic pollutants in the furthest parts of the northern hemisphere). Global warming, climate change and ozone layer depletion are clear indicators of our environment's degradation. The impact of this is likely to increase in the future having devastating consequences for the next generations and eco-systems.

Considering the time constraint for this project, the manufacturing sector - as one of the wealth creation sectors of an economy - was chosen to be investigated. As metal products constitute a large proportion of manufactured products and large amounts of energy are consumed typically in their manufacture, the sustainable manufacturing of metal products is the focal point of this research. Aluminium based products were chosen since it is the non-ferrous material which is more common on the earth and is used for many applications ranging from building to aerospace industry. .

Based on the above, this MSc thesis addresses the following research questions:

- *Which new manufacturing process concepts for aluminium products are likely to meet the economic and environmental sustainability of the future?*
- *What impacts will these new concepts have on other processes outside manufacturing e.g. impact on raw material production?*

The selection of each case study (i.e. comparisons between a baseline and different sustainable scenarios) is based on these research questions. These scenarios are:

- *scenario 1 (baseline): traditional manufacturing process, conventional equipment and 100% of electricity provided by the grid,*

- *scenario 2 (implementation of new technology): traditional manufacturing process, new equipment (reduction in material usage) and 100% of electricity provided by the grid),*
- *scenario 3 (reusing the material waste): partly-closed and/or closed manufacturing process, conventional equipment and 100% of electricity provided by the grid, and*
- *scenario 4 (electricity provided by the grid and the renewable): closed manufacturing process, conventional equipment and electricity and 95.54 % of electricity provided by the grid and 4.46 % by renewable.*

The company used to carry out this study was a manufacturer of aluminium cans.

A sustainability assessment framework available to the public domain was used to address these questions. This framework is called "Sustainability Framework Model" and was created by NACFAM (National Council for Advanced Manufacturing) which comprises environment and financial modules.

Scenario 3 "reuse of material waste" is very promising since the main emissions and raw material coming from the mines were reduced. As a result, the profit of the company for a period of 10 years has increased.

Acknowledgements

Firstly, I would like to thank GOD for patience, perseverance, and strength given during my life; and thank for teaching me that even during the adversity everything is possible.

I am very grateful to Professor Duc T. Pham for his support and patience during this process.

The help provided by the Instituto Tecnológico Metropolitano (ITM) in Medellín and Empresa Metalmecánica de Aluminio (EMMA) is well recognised. Foremost, I would like to express my sincere gratitude to Professor Ramón Fernando Colmenares Quintero for the continuous support, advice and guidance of my MSc research, for his patience, encouragement, insightful comments and hard questions.

Thanks to my British mom and my angels on earth, all of you have helped me to make my dream comes truth.

Thanks to my husband because you always believed that I could do it and also to my little king, you are my battle partner!!

Thanks to my mom, dad and my 4 brothers, you are the engine of my life.

And thanks to everyone who from one or another way supported this process.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

CHAPTER 1

INTRODUCTION: ECONOMIC GROWTH AND IMPACT ON THE ENVIRONMENT

There is strong evidence that our planet is running out of natural resources of raw material and energy which is leading to an increase in their price and limitation. The energy used to power our societies is mainly based upon fossil fuels. Firstly, global oil production is approaching its maximum value; secondly, its residual sources are more limited and found in areas which are unstable politically. According to the United Nations (UN) estimations (UN, 2007), global population will increase by a factor of 0.37 approximately for the following 42 years. Therefore, the global energy consumption will grow by about one percent per annum in accordance with the estimations by the US Energy Information Administration (2007).

Furthermore, there is increasing indication that global warming is taking place. In 2007, the Intergovernmental Panel on Climate Change (IPCC) indicated that climate change is undeniable since earth temperature growth, ice and glaciers’ melting, and growing sea levels are evident. The global warming and ozone layer depletion are the consequences of the activities of many countries. Acid rain, which is contaminating the water available on the earth (e.g. rivers and lakes) and destroying forests, often originates in one country and is placed in another. As a result, the European Union (EU) has developed a large number of environmental regulations (policies). There are more stringent regulations to come which will have an impact on the way the economy is run. In other words, it will demand that businesses are more responsible for environmental damage and be more proactive to mitigate their environmental impact.

Taking into account the above, there will be more pressure on the manufacturing industries to generate the required water, foods, services and products to maintain the earth's population (which is increasing) with less environmental impact. Also considering the time constraint for this project, the manufacturing sector - as one of the wealth creating sectors of an economy and a major consumer of energy and resources - was chosen to be investigated. As metal products constitute a large proportion of manufactured products and large amounts of energy are consumed typically in their manufacture, and the behavior of the metallurgy and metalworking sector reported an important growth in the Colombian economy so far in the decade, particularly in sales (Aktiva Servicios Financieros, 2013), the sustainable manufacturing of metal products (specifically aluminium products) is the focal point of this research.

1.1 Thesis Overall Objective and Scope

The main objective of this thesis is to find the answers for the following research questions. They are based on a literature review on sustainable manufacturing done so far. As the literature review moved forward these research questions were refined or/and extended as shown in Figure 1.1. These questions are as follows:

- Which new manufacturing process concepts for aluminium products are likely to meet the economic and environmental sustainability of the future?
- Which impacts will these new concepts have on other processes outside manufacturing e.g. impact on raw material production?

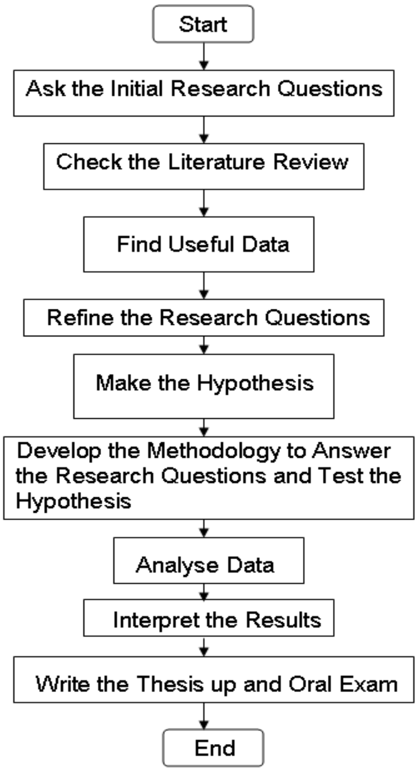

Figure 1.1 Flowchart of the project

The selection of each case study (i.e. comparisons between a baseline and different sustainable scenarios) is based on these research questions.

A sustainability assessment framework available to the public domain was used to address these questions. This framework is called "Sustainability Framework Model" and was created by NACFAM (National Council for Advanced Manufacturing) which comprises environment and financial modules. This computational tool can be used to conduct assessments for:

- Initial and detailed strategy development,
- Manufacturing product design,
- Manufacturing process strategy development and
- Manufacturing implementation

Leading to recommendations on what is achievable in terms of emissions reductions whilst still retaining the financial benefits to the company.

This study is focused on sustainable manufacturing processes. Several manufacturing process concepts are considered:

- Traditional process i.e. raw material, water, chemicals and energy which are inputs of the process, then employed during the process and leaving it as products, emissions and residual waste, and
- Partly-closed and/or closed process i.e. raw material, water, chemicals and energy input to the process or a portion of the process and all of its outputs are recycled leading to a limited amount of waste, for minimal environmental and economic impact.

The first step was to identify inputs with more significant impact on outputs by means of Taguchi experimental design technique and in a second step by analysing the traditional and more advanced manufacturing processes using more relevant inputs found in the first step.

1.2 Thesis Organisation

The literature review is given in chapter 2. This chapter summarises different concepts such as emissions, sustainability, sustainable manufacturing, manufacturing system design, existing methodologies to assess sustainability and some proposed sustainable manufacturing concepts, among others. The NACFAM Sustainability Framework Model and case studies are explained in chapter 3. The case studies are discussed in chapter 4. Finally, conclusions and recommendations are presented in chapter 5.

CHAPTER 2

LITERATURE REVIEW: ECONOMIC GROWTH, ENVIRONMENT AND SUSTAINABLE MANUFACTURING

2.1 Economic Growth and Impact on the Environment

2.1.1 Introduction

The environmental damage taking place in our world is mainly due to economic activity in the industrialised countries. Humanity's activities are contributing to the contamination of the environment which have attained global levels (e.g. the detection of trace metal and organic pollutants in the furthest parts of the northern hemisphere). Global warming, climate change and ozone layer depletion are clear indicators of our environment's degradation. The impact of this is likely to increase in the future having devastating consequences for the next generations and eco-systems.

According to ENERGY STAR Portfolio Manager (2011) the energy use (e.g. heat and power) related to economic activities in the U.S.A. represents 45% of greenhouse gases (GHG) contributing to global climate change. The main GHGs released to the environment, which come from commercial, industrial, and electricity production sources, are: methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2), which represents more than 99% of the whole GHG emission while CH_4 and N_2O represent less than 1%. Electricity consumption in commercial and industrial buildings stands for approximately three-quarters of these GHGs and the rest corresponds to the combustion of natural gas and petroleum products.

2.1.2 Economic Growth

Economic growth is an enhancement in national income per capita; in a broader sense, this involves a rise of National Income (NI), Gross National Product (GNP) and Gross Domestic Product (GDP). Therefore, this growth is the combined effect of these structural changes in the economy resulting in an increase in state wealth (Haller, 2012). Consequently the economic growth refers to the process of boosting the capability of macro-economic indicators and state economies with an emphasis on GDP per capita. The increase in size observed, may not always be linear yet, has positive effects on the economic-social segment whereas development indicates how growth affects the standard of life within the society.

Economic growth can be positive, zero or negative. If the annual average rhythms of the micro-indicators outperform the average rhythms of growth of the populations the economic growth is considered to be positive. A zero economic growth is a result of annual average rhythms of growth of the macro-economic indicators, especially GDP, are identical to those of the population growth. If rhythms of population increase are greater than those of the macro-economic indicators, economic growth is considered to be negative.

Furthermore, economic growth is an intricate process that needs to be observed over a long period of time and is bounded by constraints such as: the excessive rise of population, limited resources, inadequate infrastructure, inefficient utilisation of resources, excessive governmental intervention, among others.

It is possible to acquire economic growth by an appropriate utilisation of resources and by the expansion of the magnitude of country's production output.

Income distribution within a dynamic society is an easier task compared to a static one. If the rate of economic growth is considerable, the manufacture of goods and services increases and results in a diminishing rate of unemployment and higher standard of life for the population. In developing countries most of the population is engaged in work that is not highly productive due to the outdated economic structures. However, it is possible to transfer knowledge and resources and focus on more productive sectors.

Economic growth is focused on economic activity and visible changes (Haller, 2012). In contrast, economic development is broader and encompasses the quantitative variations that occur within the economy and society; it can also be regarded as a further development of macro-economic conditions. Typically, growth theories are utilised when referring to developed countries; the economic problems that are specific to the developing or less developed countries are explained using theories of economic development.

Net Present Value (NPV). It is used because it puts predicted future income and expenses for a potential project in terms of current monetary value, facilitating the investment decision based on a financial evaluation of a project's net worth (Baca, 2002). If the NPV is greater than zero, then the assessed alternative is good in today's money and the income is greater than the expenses; if NPV is less than zero the project will have less income than expenses which shows that the project is not viable; if it is zero, then the income will be equal to expenditures, which means it makes no economic difference. The NPV can be used in individual projects or in the alternative investment decision, in the first case it is enough to know the sign of the NPV to make the decision. It can occur simultaneously that several projects are presented, in this scenario the execution of one project excludes the possibility of execution of any others, and each must evaluate separately, whilst using the same planning horizon so that they can be compared.

According to Accounting Tools (2014), the NPV is a tool of analysis, which is useful when it is necessary to decide whether or not to invest in a project. An attractive investment has a positive NPV which means a surplus of cash to be received over time; a negative value indicates that the investment will lose money. The NPV is estimated as the variation between the actual value of one or more incoming cash flows and one or more outgoing cash flows. The discounted cash flow approach is applied to get present value, using a discount rate which is usually based on company capital cost performing the evaluation.

Internal Rate of Return (IRR). According to Baca (2002), the IRR is an index that measures the performance of an investment. Financially, the IRR is the rate at which the cash flows are discounted so that revenues and expenditures are equal, from the mathematical point of view the IRR is the rate at which NPV becomes zero.

Another definition is given by Accounting Tools (2014) as follows: ‘the IRR is the rate at which the value of a sequence of cash flows in the future is the same as the present value of the related costs.’ The IRR is normally used in capital budgeting, where the expected IRR must be higher than the capital cost. If the IRR is uncommonly high, then it is sensible to invest. On the contrary, if lower IRR rates are obtained in comparison with the rates to be earned on the securities of investment grade, then it is better not to invest.

This assessment method gives no direction in terms of which project should be chosen when there are several projects with the same rate of return. For this reason, the NPV method was selected as an economic indicator for this research.

2.1.3 Environmental Impact

Global warming. The Sun is the planet's primary supply of warmth and daylight; roughly 30% of the light received from the sun is reflected back into space either off the upper atmosphere or the ocean surface. The remaining light is absorbed by various sources and heats up the plant and makes life possible. The objects that absorb heat begin to emit thermal radiation. Typically, thermal radiation travels directly out of the atmosphere into space and cools down the earth in the process (Riebeek, 2007).

However, 100% of the thermal radiation emitted does not leave the earth and some gets reabsorbed by water vapour, carbon dioxide and other greenhouse gases. This reabsorption process has positive aspects such as keeping the earth warm, without which the earth temperature would be at -18 ^oC. Due to human activity over time large amounts of greenhouse gases have been released into the atmosphere. Greenhouse gases take a long period of time to decompose into elementary particles and the rate of decomposition is much less than the rate of greenhouse gas production as a result of industrial activity. The resulting increase in absorption of thermal radiation has made it difficult for it to leave the earth leading to the earth's temperature growth (refer to Figure 2.1).

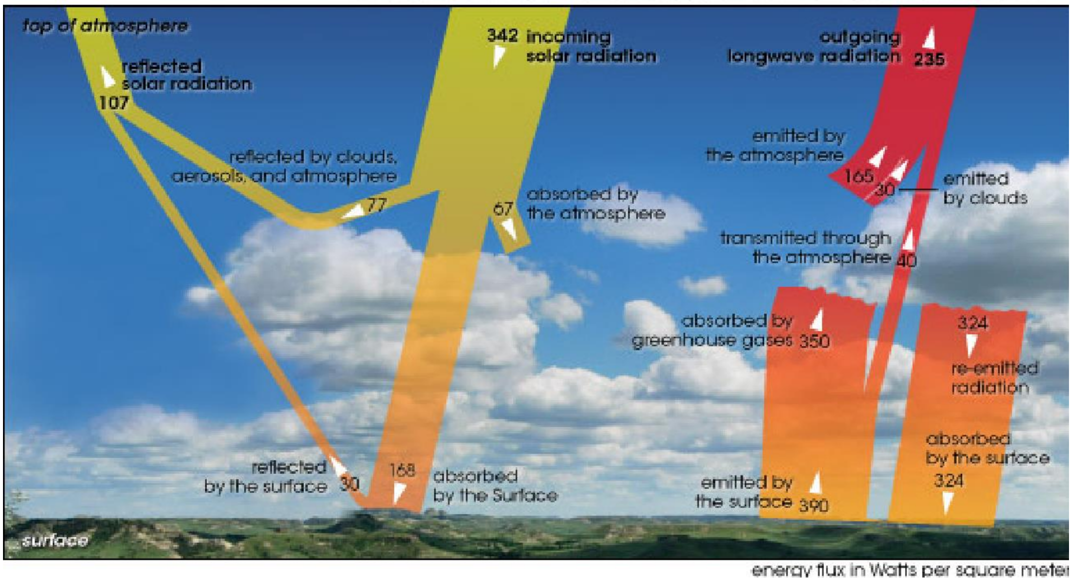

Figure 2.1 Energy received from the sun and energy emitted by the earth.

Source: Riebeek (2007).

In recent years, strict environmental guidelines have been introduced to curb the impact the chemical manufacturing; this has put a lot of focus on current manufacturing process and the industry has adopted quantitative strategies to reduce the environmental impact by minimising waste, adopting new technologies, and changes in processes and recycling of materials (Stefanis et al., 1995).

Douglas (1992), in his categorised technique, has incorporated waste minimisation using technological options to reduce pollution during the process. Using this approach, the concept related to the mass balance for the selection of processes that do not meet environmental standards was proposed by Flower et al. (1993). The incorporation of technologies called "end-of-pipe" to reduce residual waste and methods related to efficiency of mass became a key player in controlling waste as well as process design to achieve minimum waste generation (Stefanis et al., 1995).

Using the method of mass pinch, El-Halwagi and Manousiouthakis (1989) obtained optimal profitability in networks based on mass exchange with minimal pollutants. Furthermore, in 1994 Wang and Smith established a technique to achieve planned goals concerning the least waste-water production. Such methods grant access to a well ordered approach to assess the best way to reduce the generation of waste in the process; yet, these methods do not take into account the waste connected with the process inputs such as: resources, energy production, etc. Also, these methods do not have a methodical environmental assessment for several residual wastes related to the process.

Life Cycle Assessment (LCA) quantifies a full array of environmental impacts associated with a product during its whole life (Fava et al., 1991). The combination between the process-related waste assessment and the importance of the life cycle environmental impact is the attribute of this technique. Nonetheless, most of the LCA studies often involve very modest simplified manufacturing process simulations and are established on available data.

The reuse of residual waste has been examined using a life cycle approach during the last 10 to 15 years. There are publications that compare and contrast the impact of earth's warming and utilisation of energy during reuse process with landfill deposit and incineration to establish if a correlation or co-existing relationship exists and by considering certain critical factors from which valid conclusions can be derived. Four influential factors were identified in the classification between recycling, incineration and landfill deposit. The use of recycled resources almost always needs a lesser amount of energy leading to reduce the earth's warming than using raw materials coming from the mines. The incurred saving, when utilising non-renewable materials, are comparatively much higher. For example, for paper products, nevertheless, recycling savings are smaller; the differences between recycling and incineration of paper are susceptible to the quality of the paper.

Environmental interest has guided people to intensify the recycling of materials; however there is a pending query, if waste material reuse is the best alternative. This question has several scopes such as social, environmental, economic and technical; nonetheless if the main goal of waste material reuse is to reduce both resource utilization and the environment degradation, then the query must be focused on a life cycle viewpoint to reduce the possibility of worst performance. LCA examines features related to the environment and its impacts through the life cycle of a product (ISO, 1997).

Furthermore, LCA examines services, e.g. waste management (Finnveden, 1999). The main attribute of LCA is that the products being compared must offer similar functionality, in order that they can be assessed on a fair basis. Varying waste management strategies might allow several outputs e.g. energy or recycled materials. An impartial evaluation of the diverse approaches needs to be considered in the assessment (Ekvall and Finnveden, 2001). The International Standard norms advise that environmental advantages of recuperated materials be justified by increasing the borders of the system to add the excluded problems of traditional manufacture. Since the start of the 90s, LCA has been utilised to compare tactics of waste management and recycling of materials with other waste management strategies.

2.1.4 Methodology for Estimating Greenhouse Gas Footprint

***The Portfolio Manager Methodology*.** This takes into account all CO_2, CH_4, and N_2O emissions related to the energy consumption in buildings (ENERGY STAR Portfolio Manager, 2011). This methodology involves both GHG emissions generated on-site (known as direct emissions) and off-site (known as indirect emissions – at power stations) due to the combustion of fossil fuel. A default fuel analysis technique is applied to calculate the direct emissions which use factors related to fuel such as: heating value, carbon content and carbon oxidation. In the case of indirect emissions from district energy usage associated with heating and cooling, a similar method is employed. However, indirect emissions owing to electricity usage are estimated by means of direct measurement by public utility owners and operators which must send continuous emissions monitoring system data to the regulatory bodies (i.e. EPA – Environmental Protection Agency in the US) (eGRID, 2007).

A default fuel analysis technique gives a very simple calculation of direct CO_2 emissions, but when assessing the direct CH_4 and N_2O production, the process is more difficult. The reason for that is the CO_2 emissions depend upon fuel type while CH_4 and N_2O emissions depend upon combustion technology (e.g. combustor size, operation, maintenance, among others), combustion conditions, application of pollution control equipment and atmospheric conditions, in addition to fuel type. Nonetheless, since these emissions represent only a small fraction of the total greenhouse gases emitted by a building, factors related to fuel are appropriate to calculate the CH_4 and N_2O production.

To standardise the total GHG emissions reported, the amount of each gas should be multiplied by its Global Warming Potential (GWP) (CH_4=21, N_2O= 310, and CO_2=1,), and given in CO_2-equivalents (CO_2e) (IPCC, 1995). The total GHG emissions are related to the fuel consumption at the building level without taking into consideration any pre-combustion emissions generated due to fuel extraction, processing and delivery to the building.

2.1.5 Solid Waste Management

Waste Prevention. This is, in essence, a strategy to "reduce waste by not producing"; sometimes this is referred to as source reduction strategy, and conserves resource. Some strategies of waste prevention are: buying lasting goods and searching for packaging and products free of noxious matter. End aim of this strategy is to reduce the rate of greenhouse gas production and protect the environment.

Recycling. It utilises materials transforming them into useful resources that would otherwise be waste. It also mitigates the greenhouse gas production due to the reduced amount of waste in the landfills.

***Composting*. ** This is another form of recycling. It works as a natural fertiliser decreasing the requirement of chemical substances in agricultural tasks.

Combustion. It is the coordinated incineration of waste in a pre-determinate place to decrease its volume and in certain instances to produce electricity. The generation of very harmful emissions can be restrained by putting in a special device. The solid waste incineration decreases the quantity which ends up in dumping grounds and reduces the dependency on coal, which is a greenhouse-producing fossil fuel.

Landfilling. Unrestricted depositing of waste contaminates groundwater and soil, bringing plagues like rats and insects. The decomposition of waste generates methane which is a greenhouse gas. It is necessary to design landfill sites with an earthen or synthetic liner with adequate ventilation and methane collection. The recovered methane can be used to generate electricity and reduce the emissions.

2.1.6 Sustainability

The sustainable development concept appeared for the first time in the 1970s due to the growing pollution and usage of energy and natural resources. According to Redclift (1989), the word ‘sustainability’ refers to the way resources are arranged, such as: economic, environmental, social, technological and scientific, to lead to equilibrium of the whole system. On the other hand, sustainable development is a development which facilitates all the earth’s population to meet the current basic needs and have an improved quality of life without putting at risk the ability to meet the needs and quality of life for future generations (Brundtland, 1987 and Engineering Council UK, 2009).

Sustainable development is based on two concepts: needs and limitations (Engineering Council UK, 2009). An example of the former can be the basic needs of the poorest around world, as for the latter can be the limitations forced by the technology level and social organisation on the capacity of the ecosystem to satisfy the needs for the present and the future.

2.1.6.1 Challenges of Sustainability

The key challenges in sustainability are described as follows:

- Broader approaches to sustainability are needed.

- Recycling of extra products applying “reverse supply chain”.
- From the point of view of sustainable manufacturing simulation, there is a gap in terms of sustainability information sources, its metrics and indicators, a reference model for comparison and computational models among others.
- Design of the process.
- Dynamics classification and the use of the control techniques in supply chains causing an improvement in receptiveness.
- Verification fields, management of irregular situations and operating procedures development.
- Enhancement of predictive control for an effective plant model to be coupled with planning and supply chain optimisation tools.
- Inclusion of planning, scheduling and control at either plant or supply chain level.
- Supply chains design regardless of industrial reorganisation.
- Development of efficient methodologies for design of environmentally-friendly products and processes in the chemical industry.
- Environmental assessment of the product design and the processes.
- Changes in the design process and the manufacturing procedures applicable to the next generation products.
- Introduction of the scientific approaches and employments of the whole life cycle of manufactured products.

2.1.6.2 Sustainability in Colombia

According to the Organisation for Economic Co-operation and Development (OECD) (2014), Colombia is one of the most bio-diverse countries in the world, since it has a rich natural legacy; but it is under pressure from extractive industries, livestock grazing, urbanisation and use of cars.

The first analysis of environmental performance made by the OECD in Colombia revealed the necessity to do more to guide economic development in an environmentally sustainable and socially fair route. According to the Environment director of the OECD, Simon Upton, the economic growth in Colombia has accelerated and one of the actions needed is to protect one of the richest ecosystems and forests in the world. Also, a key solution will be bringing environmental strategies in line with the best international practices.

The dependence on hydroelectric power has resulted in low CO_2 emissions in Colombia, but the increase in the use of cars means more emissions and more air pollution. On the other hand, the strong economic growth in Colombia is partly due to the extraction of oil, metals, minerals and coal for export; the disadvantage of this is that these industries pollute the soil and water damaging ecosystems and human health. As a result, it is necessary to improve the management of environmental impact of the mining industry.

The inundations and avalanches associated with the 2010-2011 La Niña experience that involved 3 million people and decreased GDP by 2%, emphasised Colombia's exposure to climatic variations and impelled attempts to better incorporate environmental issues into economic strategies. Nonetheless, it is possible to do more to enhance consistency between economic and environmental regulations. The assessment advises that regular environmental considerations are reviewed for major projects.

Colombia is extremely exposed to intense weather incidents and slash-and-burn agriculture, non-natural drainage of wetlands, deviations of natural rivers routes and the construction of communities and cities in zones at risk of inundations or avalanches will intensify the threats. Roughly 55% of Colombia is covered by jungle and deforestation is having a big impact on the Amazonian, Caribbean and Andes zones. The deforestation level lately dropped, but 30% to 50% of natural ecosystems have been modified somehow. Moreover, a third of greenhouse gas emissions produced in Colombia is due to agricultural activities, methane is produced by livestock and the nitrous oxide emissions from artificial composts i.e. fertilisers.

2.2 Sustainable Manufacturing

Manufacturing (one of the key economic activities which has a direct impact on the environment) describes a process of transforming raw materials, parts or components into products which satisfy the requirements of a client. On the other hand, sustainability is understood as the way to achieve alternatives where resources are used efficiently in order to reduce the negative impacts on the ecosystem. The combination of these two concepts i.e. sustainability and manufacturing, generates the sustainable manufacturing (SM) definition expressed as follows: The essence of strategies to transform resources without causing negative impacts on the environment.

In 2009, an interesting description of SM was given by NACFAM (National Council for Advanced Manufacturing) which consists of two parts: the manufacturing of sustainable products i.e. renewable energy, energy efficiency, green building and so on, and the manufacturing based upon a series of sustainable processes applicable to all the products. Moreover, the US Department of Commerce characterises SM as the process of making products while minimising the environmental impact, the consumption of natural resources and energy.

These concepts and definitions allowed several techniques or methods to be developed. The methodologies available in the public domain are described in the following section.

In the development and production of new goods, sustainability is an approach commonly recognised but little used. The incorporation of environmental needs during the course of the lifecycle of the product requires new thinking and new decision tools.

In the product development process, the introduction of environmental specifications throughout its lifetime leads people to a new sustainability concept showed in a new mental model, tools and strategies. These environmental needs should be considered at the same level of cost and quality (H. Kaebernick et al. 2003).

2.2.1. Existing Methodologies

The Sustainable Standard Portal (2010) gives an overview of the product life cycle which can be divided into two cycles as depicted in Figure 3: the first one represents the acquisition of materials (i.e. extraction and processing) from the planet and then disposal of waste again; the second one includes the pre-design, production (manufacturing), use, and post-use of the product.

There are various methodologies which have been applied successfully to sustainable manufacturing in the second cycle described above. These can be classified into three groups: product-related, process-related and direction or management-related.

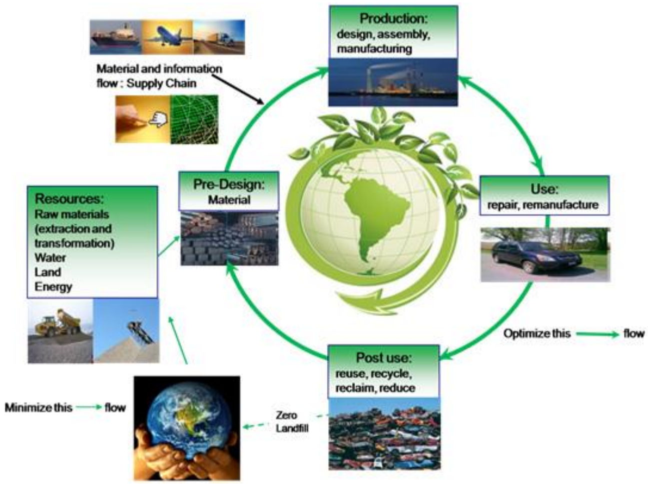

Figure 2.2 Sustainable manufacturing cycle. Source: Sustainability Standards Portal (2010).

The application of the SM methodologies has been analysed through five steps of the product life cycle defined by the Sustainable Manufacturing Portal (2010) (refer to Figure 2.2).

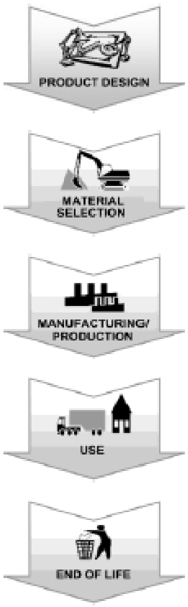

Figure 2.3 Life cycle representation. Source: Sustainability Standards Portal (2010).

As can be seen in Figure 2.3, the first two (i.e. product design and material selection) are product related whilst the remainder i.e. manufacturing/ production, use and end of life, are process related. The management-related group encompasses the product- and process –related sets, and the product end-of-life becoming the whole life cycle.

2.2.1.1 Product-related Methodologies

Product Design. It starts with considerations such as: current needs, client requirements and benefits brought by product. Then, the environmental impact of the designed product needs to be assessed. There are two techniques employed in the evaluation of the environmental impact of a product during the design stage, namely: LCA (life cycle assessment) and Eco-design.

LCA is a technique that identifies and quantifies the use of resources (raw materials, energy, etc.) as well as waste in the manufacturing process while the Eco-design technique reduces the environmental effect during the design process of a product keeping its purpose constant.

A vital point in manufacturing is the development of sustainable methods; one of the key strategies to achieve this is the practice of design for the environment (known as Eco-design) for instance by means of increasing the efficiency and effectiveness in remanufacturing which is a process of harmonisation of ‘used products’ to an “almost-new” functional condition (Winifred L. Ijomah et al., 2007).

Remanufacturing is not well-known in world economies and is inadequately understood due to its freshness. But environmental pressures are changing the world and the business context leading to the interest in this practice.

Material Selection. The selection of materials is not an easy task as they need to satisfy requirements demanded by the design and market as well as aspects such as price, easy processing, and disposal among others. Furthermore, the proper choice of material will influence the environment since some chemical substances contained in the material can be harmful to it.

2.2.1.2 Process-related Methodologies

Manufacturing/Production. The manufacturing processes (with their inputs, technology and structure) and their impacts (in terms of pollution, waste, profitability, etc.) need to be assessed at product life cycle level i.e. material production, product design level – so-called upstream impacts- and distribution and customer use – so-called downstream (see Figures 2.4 and 2.5). The reason for that is as follows: there are companies that claim that they manufacture environmentally friendly products, however the process of their manufacturing may be unfriendly i.e. they may have been produced using: energy in a negligent manner, and non-renewable resources, as well as in their disposal after being used.

In the developed nations, the life cycle of new products, higher labour costs and expectations of customers, including the upgrade of products with the latest features, affect the increase rate of products being discarded (Sev V. Nagalingam et al., 2013).

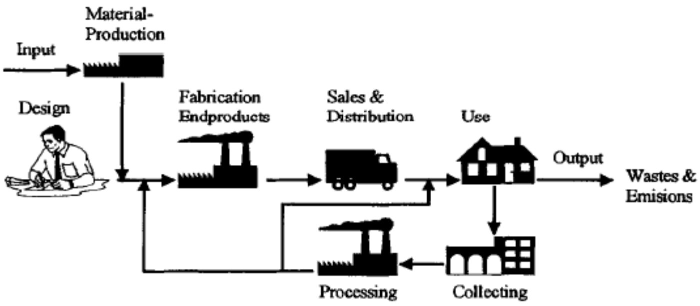

Figure 2.4 Different stages of the product supply chain. Source: de Ron (1997).

In order to mitigate the destructive impact on the environment, it is required from manufacturers to design sustainable goods to apply systems of cleaner production for 3 R, i.e. Reuse/Remanufacture/Recycle, processes (refer to Figure 2.6).

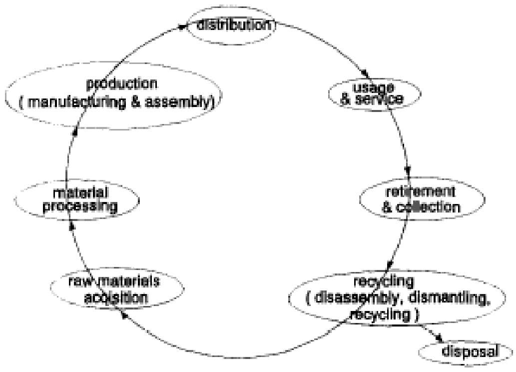

Figure 2.5 Product life cycle. Source: de Ron (1997).

Nonetheless, metrics are still needed to assess returns of the products with recovery adjustments. A methodology based on Six Sigma is proposed by Sev V. Nagalingam (2013) to calculate the value related to the use of manufactured products with recovery adjustments representing the lead times of production, the waste minimisation, the full recovery cost, and the quality (see Figure 2.6).

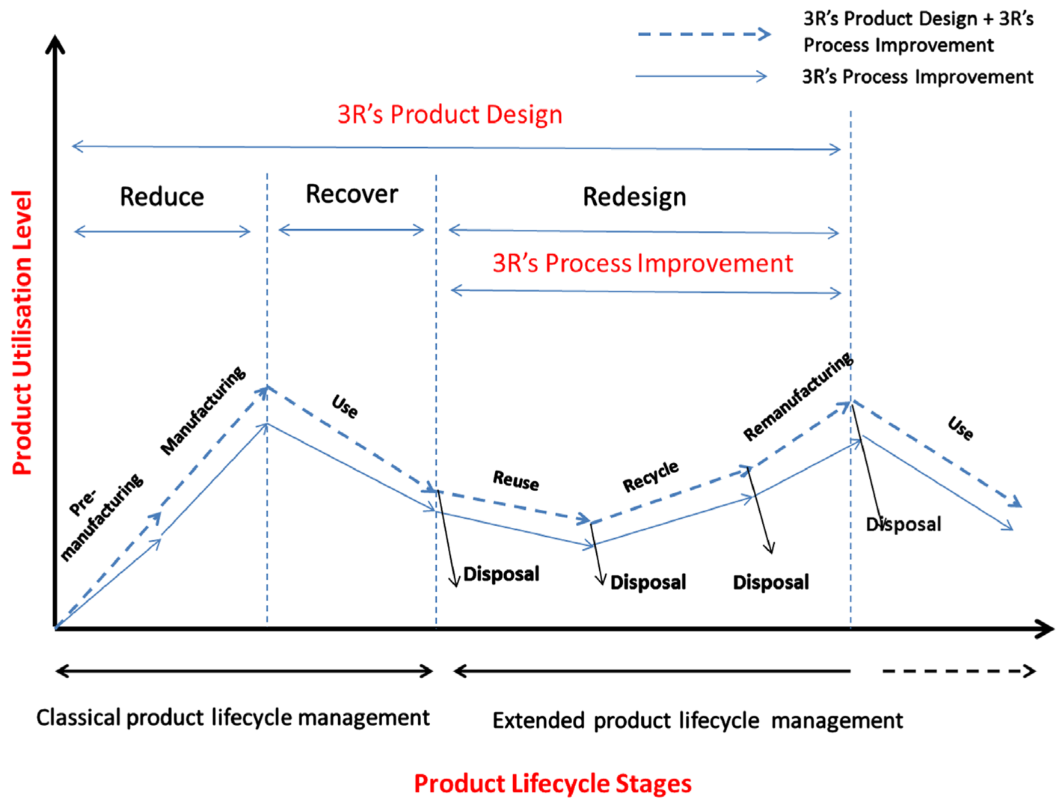

Figure 2.6 Value of product utilisation by introducing 6 R methodology.

Source: V. Nagalingam (2013).

2.2.2. Sustainability Assessment for Manufacturing Sector

There are several research papers about sustainability assessment for manufacture available in the public domain. The most relevant research is shown as follows:

A methodology for life cycle and sustainability analysis of manufacturing processes emphasizing the flexibility and decision-making process using knowledge base systems is defined by Culaba and Purvis (1999). This methodology is focused on on-site waste minimisation and sustainability features related to environmental impact and process enhancement. The derived computational model was employed with certain success to an initial assessment of pulp and paper manufacture.

Ad J. Ron (1998) introduced a sustainability assessment in order to examine the actual condition of companies regarding sustainable manufacturing and to set their objectives. A series of performance indicators have been defined to measure several items relating to efficiency, quality and flexibility. In addition, a five-step assessment, which is made up of organisation and planning, pre-evaluation and feasibility study and implementation and continuation, is given.

An overview of new concepts and trends in sustainable systems, processes and products is shown in Jayal et al (2010). It points out that in order to attain sustainability, as a whole, a holistic assessment is needed bearing in mind the complete supply chain along with manufacturing systems and processes, and different product life cycles. Additionally, it is focused on the development of enhanced methods for evaluating the sustainability of products and processes, computational models and optimisation approaches used in sustainable manufacturing processes for dry, near-dry and cryogenic machining.

An environmental assessment of industrial districts (IDs) was performed by Albino and Kühtz (2003) applying an input-output accounting model based on principal energy and materials flow inside an industrial district. This model calculates resources and energy used as well as wastes generated within the system. This information is very relevant in guiding the managers of the companies in the decision-making process in terms of sustainable development objectives concerning the local areas. Besides, information vis-à-vis strategies for recovery, recycling and re-use can be obtained. Two case studies applicable to the industrial districts of Sassuolo and Matera in Italy were analysed for tiles and leather upholstery manufacture. The advantage gained, in the ID of Matera, via burning wood wastes to generate electric and thermal energy is related to the resulting rise of CO_2. These kinds of environmental assessment, performed in a simple and effective manner, are appropriate to find out which product or process within the system has the highest effect on the environment. The key concern is still the data collection, however this approach can be beneficial to the companies and the public bodies to determine what is achievable in terms of sustainability.

A recent analysis of the eco-efficiency regarding manufacturing industry in the States was carried out by Gokhan Egilmez et al. (2013). The methodology used for this study was based on an integration of a linear programming-based optimisation tool, DEA (Data Envelopment Analysis) and EIO-LCA (Economic Input-Output Life Cycle Assessment). First of all, the EIO-LCA model computes water and energy usage, greenhouse gas (GHG) emissions, hazardous waste and toxics generation for every manufacturing sector. Then, a DEA model was developed, followed by the definition of marks and levels for eco-efficiency, rates of goals and operation enhancement. Lastly, the sensitivity analysis was carried out. The conclusion of this study was that five manufacturing sectors i.e. food, coal and petroleum products, printing, accessories, and cars, were 100% environmentally-efficient. Conversely, roughly 90% of these sectors in the USA were found to be inefficient. As a result, their life cycle performance needs to be improved. The energy usage had the biggest impact on the eco-efficiency of these sectors, hence the following recommendations were given: enhance energy efficiency in manufacturing processes and increase the use of renewable energy.

In the metal production field, the evaluation of the environmental impacts of its processes is often hard to achieve owing to numerous inputs and outputs implicated. Norgate et al. (2007) applied Life Cycle Assessment as a strategy to pinpoint the key activities during the metal production life cycle which contribute to environmental degradation. The analysis was made for aluminium, nickel, copper, lead, zinc, titanium, steel and stainless steel using pyro-metallurgical and hydro-metallurgical methods. The environmental performance analysed of the metal production processes involves greenhouse gases, acid rain and solid waste. Advanced technologies which are expected to decrease the environmental impact are also discussed in this study.

There is a broad variety of methods to improve the manufacturing efficiency for example Just in Time (JIT) or a series of lean manufacturing approaches. The choice of the right methodology to enhance manufacturing is a big problem for various enterprises, as well as its relevance, integration and adoption within operations (Herron et al, 2006).

An approach has been developed by (Herron et al, 2006), which is made up of 3 steps: first, analysis of the needs for productivity (PNA) providing a general idea of the state of manufacture situation of the enterprise, second recognition of key metrics for productivity at the facility level, and third set-up of the ground for an in-depth analysis of manufacturing efficiency.

Processes and difficulties in the plant are established and linked with the proper approaches and indicators in the Manufacturing Needs Analysis (MNA) creating a yearly preliminary improvement plan for a specific production unit. Some of these difficulties found in the companies were: small capacity, programming and innovation in products and processes; such difficulties are not directly influenced by lean manufacturing methods. But they involve a group of losses: planning/WIP (work in process)/inventory levels, rework/ defects / performance and downtime / set-up/ lost efficiency which are related to each other.

A usual procedure in emerging nations is to introduce used manufacturing structures and use them again for more production cycles. A multi criteria decision methodology was developed by Ziout et al., (2012) to evaluate the advantage of re-using manufacturing structures employed in an emerging nation, taking into account the three main aspects of sustainability: economic, social and environmental.

Cheap labour and energy in emerging nations lead to the reuse of existing manufacturing methods in a more workable manner regarding sustainability. A study carried out with this respect displays that economic sustainability is the principal motivation of decision makers in these areas whilst environment has the smallest impact. These results put on alert both legislators and policy makers to take action in terms of more care and severe policies to stimulate environmental sustainability (Ziout et al., 2012).

To achieve the premise "satisfy the requirements of present generations without putting at risk the ability of future generations to satisfy their own requirements" only can be accomplished by using resources sustainably. Manufacturing has a vital responsibility in sustainable development since actually the manufacturing system is considered the cornerstone of sustainable growth. The amount and nature of resources used in manufacturing systems (structures) are associated with manufacturing utilisation, emissions and waste.

The recycling of a manufacturing structure after its first cycle is a critical issue that must be evaluated carefully. The economic, environmental and society´s sustainability of this structure must be analysed before starting another cycle of use.

It was possible to determinate that the importance of each element of sustainability is not identical; it depends on the development urgency of the country implementing the employed manufacturing structure. In the case of developing countries, economic sustainability was the most important aspect followed by social and environmental sustainability.

There are significant challenges to recognising and understanding the social effects related to manufacturing processes. Social impacts are presented at different levels e.g. system and company, in manufacturing. These impacts affect the final customers, regions and even politics (Hutchins et al., 2013).

To analyse the social impacts of the manufacturing effectively it is crucial to do the following (Hutchins et al., 2013):

- Establish the scope of the company in which the processes happen, through the phases of the product life cycle and the processes involved.
- Define if it is the product or process that matters.
- Use a specified group of factors to identify social impacts and hazards related to manufacturing.
- Evaluate the root of the problems identified and thus establishing the ground for addressing them focused on their impacts.
- Recognise decision makers with the aptitude to cause positive transformation or create groups with the capacity to develop holistic solutions.

2.2.2.1 Sustainability Indicators

Composite index and Sustainability indicators have been accepted as a convenient instrument for people, who make policies and public communication in transmission of information to the nations and corporate operation in areas such as society, environment, and economy (Singh et al., 2008) Sustainability values measure, abbreviate, examine and transfer complicated data. There are many people working on ideas and structures for sustainable development.

It has been treated to collect data regarding how the indicator was expressed by the use of three stages, normalisation, weighting, aggregation. It is possible to say that normalisation and weighting of indicators are related to particular findings, expose a high level of uncertainty and not critical supposition. While for aggregation it is possible to use scientific assumptions that assure the uniformity of the composite indices, the main advantage of composite indexes is the multidimensionality. The indexing of composite materials is complex, and there is very little interest for considering environmental, social and economic aspects in the measurement of sustainability.

Composite indicators can lead to erroneous messages if they are poorly constructed or misinterpreted. Different stakeholders should agree which indicators associated with sustainable development need to be considered.

Nowadays, complex and simple indicators are accepted as powerful instrument for policies formulation and data transfer about a nation's operation on areas like environment, economy, society, or technological development.

According to Meadows (1998) indicators come from quantities – it is assessed what people are interested in - and those indicators generate quantities – people are looking after what it is assessed. Godfrey and Todd (2001) define the key characteristic of indicators as their capability to abbreviate and group the huge complex dynamic environment in a controllable volume of useful information. Warhurst (2002) explains that indicators abridge measure, assess and show complex information by means of phenomena representation and their tendency.

There is a big demand for people, associations and institutes to establish patterns, metrics and instruments to express the magnitude and tactics in which the present actions are unsanctionable. This requirement results from supra-national, national, and sub-national stages (Ramachandran, 2000). There are seven important questions to explain sustainability science but two of them have a special connection with sustainability that matters (Kates et al., 2001):

- ‘‘How can today's operational systems for monitoring and reporting on environmental and social conditions be integrated or extended to provide more useful guidance for efforts to navigate a transition toward sustainability?"
- "How can today's relatively independent activities of research planning, monitoring, assessment, and decision support be better integrated into systems for adaptive management and societal learning?’’

The objective of sustainability evaluation is to offer decision-makers an estimation of a worldwide view of particular natural and societal systems over short and extended periods with the purpose of better defining the facts that can or cannot be considered in an attempt to create a sustainable culture (Kates et al., 2001).

In Warhurst (2002) sustainable development is proposed to be evaluated in a two-level method. First of all, the improvement made in an amount of some selected, single zone is calculated by sustainable development indicators (SDIs) and then the general improvement made regarding sustainable development is evaluated by a mixture of those single zones regarding their interconnections. In 2000, Lancker and Nijkamp express that a known indicator means nothing regarding sustainability, unless a baseline or threshold quantity is assumed. The SD indicators might be applied as follows (Lundin, 2003 and Berke and Manta, 1999):

- To predict and evaluate circumstances and tendencies.
- To afford initial data to avoid economic, social and environmental breakdown.
- To create tactics and share concepts.
- To help decision-making.

Lundin (2003) states that once a structure is created and the SDIs are chosen, two different methodologies can be appreciated:

- The 'top-down' method indicating that specialists and scientists describe the structure and the group of the SDIs.
- The 'bottom-up' method, which takes into account the contribution of several participants in the proposal of the structure and the SDI selection procedure.

To address the difficulty of deficient physical interactions related to people and environment, the idea of an indicator called "socio-ecological (SEI)" was presented by Holmberg and Karlsson in 1992.

A structure called "Pressure State Response (PSR)" founded on this causality model: people's actions produce effects (the "pressures") on the environment altering the quantity and quality of raw materials (the "state"). People's reactions to these effects are by generation of policies for economy, environment and sectors. These reactions are called the "societal response"). Figure 2.7 shows this PSR- structure of OECD (Organisation for Economic Co-operation and Development).

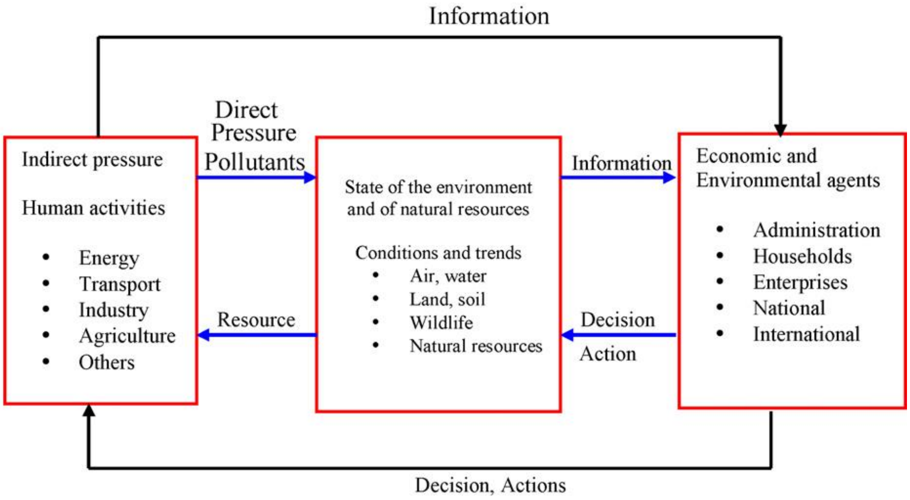

Figure 2.7 The pressure-state-response structure. Source: OECD (1998).

The Driving Force Pressure State Impact Response (DPSIR) structure is an enlargement of the pressure-state-response structure and was accepted in 1997 by the European Statistical Office and the European Environmental Agency (EEA). Figure 2.8 depicts the five features and their relations.

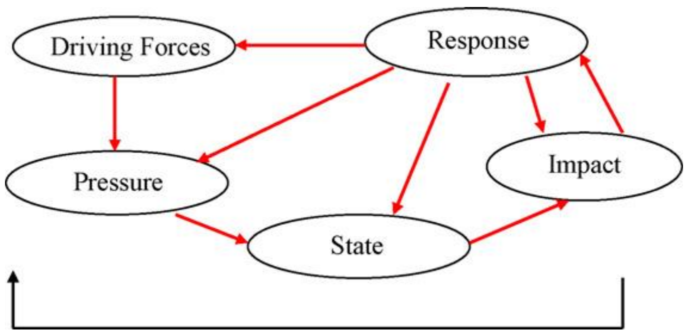

Figure 2.8 The structure of the DPSIR. Source: Smeets and Weterings (1999).

For the purpose of assessing concurrently the environmental and social elements of sustainable development, the sustainability test was created (Prescott-Allen, 1995). It is made up of two factors, so-called “ecosystem well-being” and “human well-being”, which need to be enhanced to attain development in a sustainable way. The environmental mark assesses the entire land zone needed to meet requirements of individual, product or town regarding water, food, energy and dumping of waste (Wackernagel and Rees, 1996).

The eco-efficiency structure of the World Business Council for Sustainable Development (WBCSD) tries to evaluate improvement regarding economic and environmental sustainability by the utilisation of indicators which are significant and vital for business (WBCSD, 1999).

The LCSP (Lowell Centre for Sustainable Production) structure emphasises the environmental, health and safety features of sustainable manufacturing (Singh et al., 2012). It proposes five stages in the development process going to high-level indicators of sustainable manufacturing as shown in Figure 2.9.

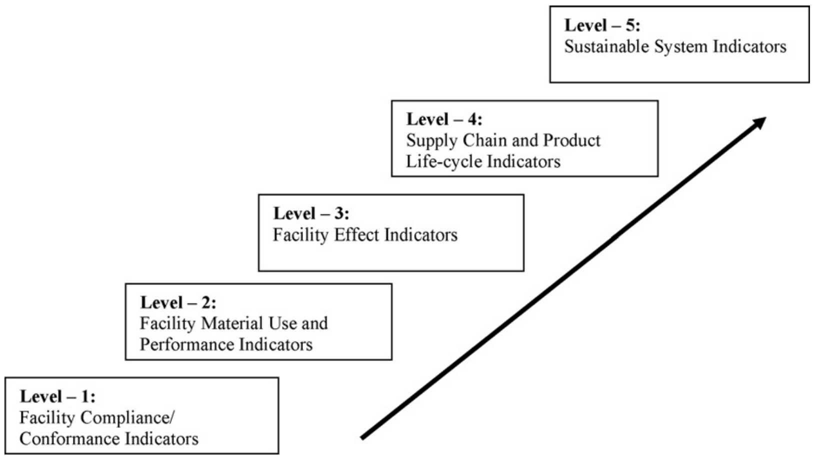

Figure 2.9 Lowell centre for sustainable production indicator framework.

Source: Singh et al. (2012).

To guarantee improved and applicable stages in favour of sustainability, the development and faults must be checked and calculated. Metrics for sustainable development are a field where numerous research and handy efforts have been carried out. The indicators must not be confused with the methods and models, since these indicators do not give straight support in carrying out sustainable development, nevertheless they describe the structure and function as metrics and give a feedback mechanism for the whole procedure.

The Coalition for Environmentally Responsible Economics (CERES) and the United Nations Environment Programme (UNEP), in 1997, introduced so-called GRI (global reporting initiative) with the aim of improving sustainability information. This report is a very important source of the recommendations and employs a ranked structure in three main topics: economy, society and environment as presented in Figure 2.10.

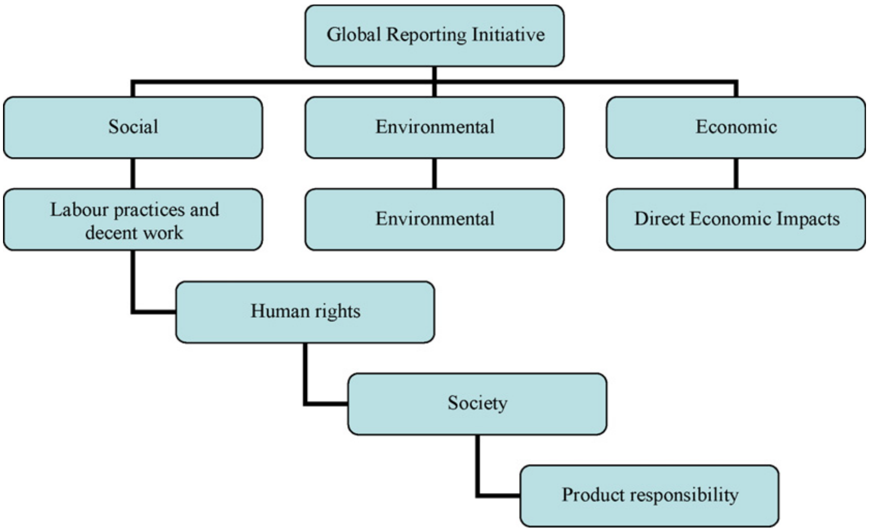

Figure 2.10 The organisation of the GRI structure. Source: GRI (2002a).

The structure proposed by the United Nations Commission on Sustainable Development (UNCSD), is based on a sustainability indicator for the assessment of governmental evolution in terms of sustainable development achievements. A categorised structure gathers indicators in 15 important topics and 38 sub-topics, separated into four parts of sustainable development as shown in Figure 2.11.

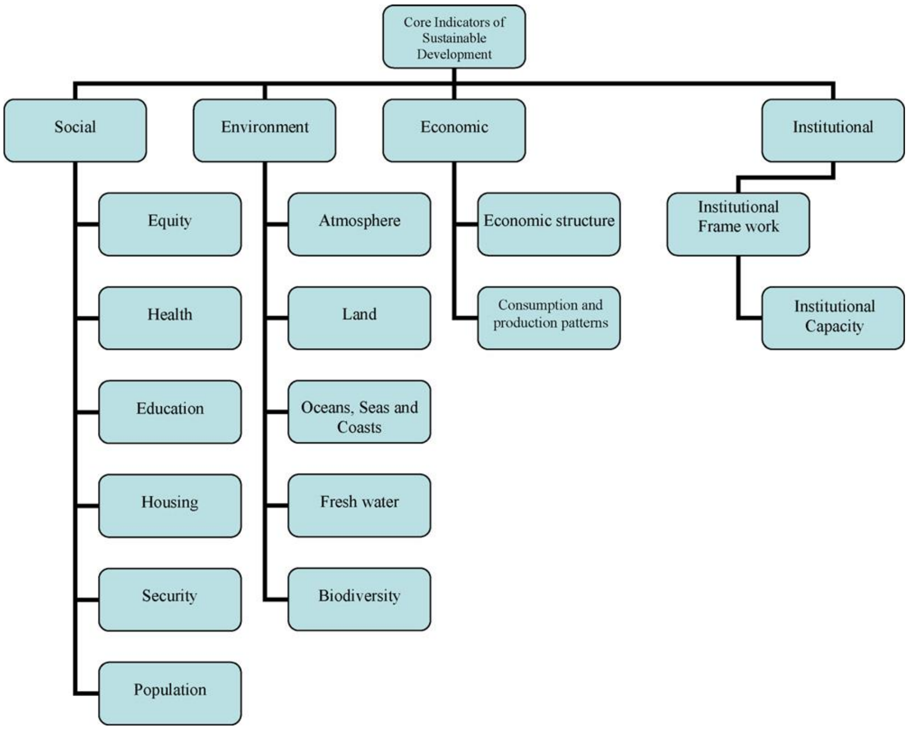

Figure 2.11 The structure for United Nations sustainable indicators.

Source: Singh et al., (2012).

It is possible to find two kinds of strategies to measure sustainability: the 'monetary aggregation' method used by economists and the 'physical indicators' selected by researchers and scientists. The former incorporates greening the gross domestic product, modelling for sustainable growth, resource calculation centred on their role, and expressing fragile and solid sustainability states. The economists adopt sustainable growth as a section related to the economy`s sustainable development.

Following the neoclassical model which suggests that the economic well-being is evaluated focused on the consumption level models – which assess sustainable growth -

try to find a non-decreasing per capita utilisation approach based upon an ideal employment of technology and resources.

The requisite for sustainable revenue, so-called Hicks/Lindahl, is non-decreasing worth of the total stock issued by companies throughout time. A fragile sustainability situation adopts the ideal replaceability among natural and manufactured resources, and a solid sustainability situation adopts no replaceability.

With respect to the Solow-Hartwick structure, the route for sustainable increase is not the same as the route for the best increase implying that sustainability might be attained at the expense of efficiency.

The topic of ecological economics structures is the result of socio-economic and ecological co-evolution. According to Pezzey (1992), neoRicardian approaches for sustainability search for constant conservation and mutual restoration of environmental and economic structures.

When referring to natural resources, few economists apply traditional capital assumption which recognises the probability of natural resources undergoing transformation. Principal economists choose monetary valuation as it characterises the lack of valuable resources.

A holistic structure built by Ness et al. (2007), which evaluates sustainability, is made up of three parts: indices and indicators; product related assessment tools; and integrated assessment (compilation of tools based on project execution or policy amendment) (refer to Figure 2.12).

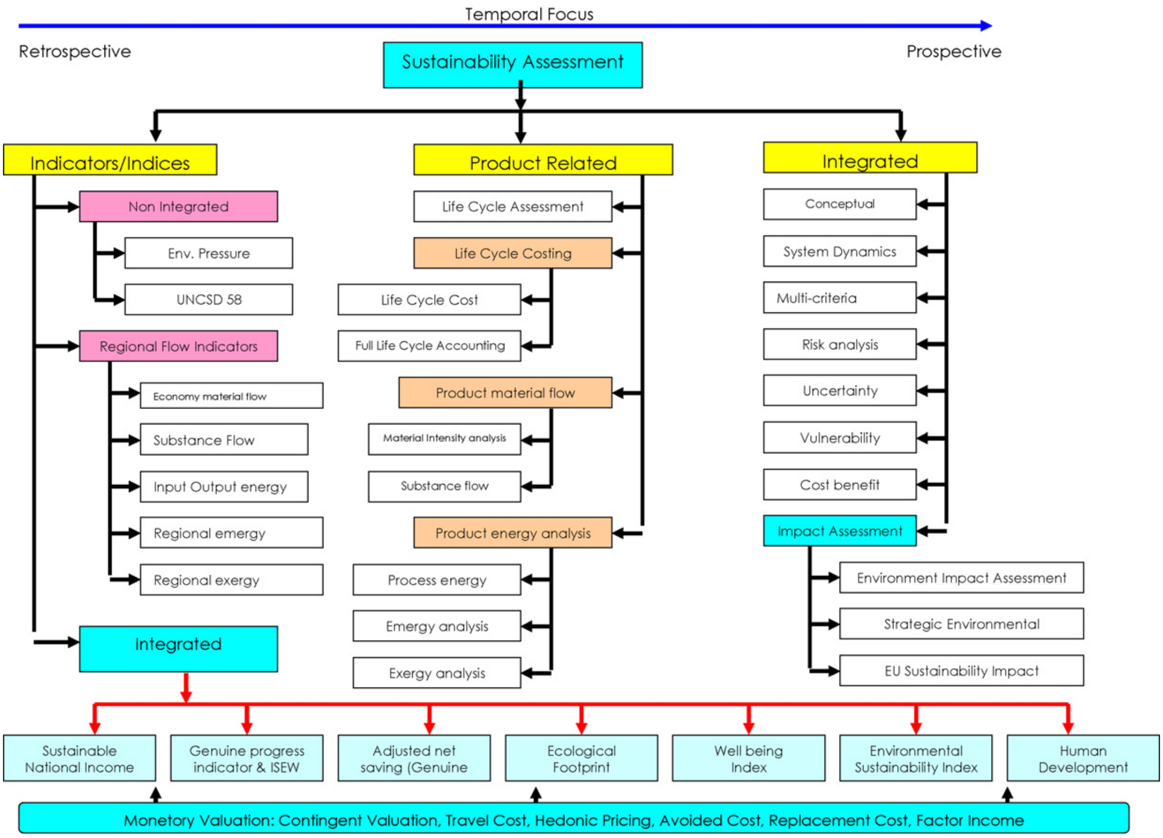

Figure 2.12 Sustainability assessment approaches. Source: Barry Ness et al. (2007).

The manufacturing sector is looking for an accessible, complete and impartial group of indicators to assess the sustainability of manufactured goods and manufacturing processes. There are a huge amount of indicators but these indicators have encountered difficulties in terms of recognising interconnected language, and choosing particular indicators for several features of sustainability.

It was proposed to group indicators and to develop an indicator classification for sustainability assessment. The aim of the classification is to proceed as a structural and instructive tool for the manufacturing sector. The exposed construction of classification is an indicator found to have more than 200 indicators contained by five sustainability aspects. In addition to that, this classification is adaptable and customisable.

In the classification, a wide analysis of actual, offered indicator groups and indices were executed. Incorporation and classification of these indicators into an organised plot and store were made by initial assessments of the comparative significance of the indicators for a manufacturing initiative per organisational and/or product sustainability assessment.

The big global issues which are tackled today require consideration of the complex situation of economy, society, environmental and technology (ESET). Recently the demand for sustainable development (SD) and its application has risen. With this conviction, added value, lean-based, competitive sustainable manufacturing (CSM) has been broadly contemplated as a principal facilitator.

The Reference Model for Proactive Action (RMfPA) method has been suggested to improve and apply CSM, at state and worldwide level. Additionally, there are approaches to practise CSM at the macro-meso-field stage.

The analysis of the European Union (EU), Japan the United States (US) and China using the RMfPA indicates that the Strategic intelligence (SI) production process is somehow recognised as well as the practical position of E&RTD&I (education and research, technological development and innovation) frameworks. In addition, at meso stage, current actions are producing paradigms and enabling technologies (ETs) for CSM.

At a worldwide level such procedures can take place, but the growth and development level of nations have to be taken into account. Coordination/integration of these may run to "clouds of countries moving at different speeds towards CSM."

2.2.3. Manufacturing System Design

According to Harrel and Tumay (1995), a manufacturing system consists of entities (i.e. inputs and outputs), resources (e.g. raw material, energy and human beings), activities (tasks), controls and processes (see Figure 2.13).

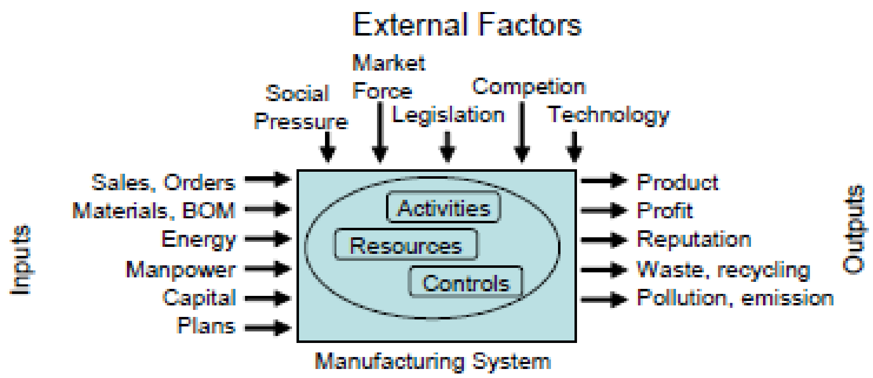

Figure 2.13 A manufacturing system. Source: Heilala et al. (2008).

Manufacturing system design includes different topics such as: system dimension, material handling, tooling strategy, process flow configuration, flexibility (in case of future capacity and engineering changes), and area strategy among others. In addition, it deals with details such as: how, where and when a process is to be carried out as well as it chooses the appropriate equipment and resources to complete the process flow.

Manufacturing process design is a key part of the manufacturing system as any decisions made during this phase will influence its future behaviour and any modifications, once the system is operating, could be very expensive. Material handling is another subject that requires a special attention since it makes possible the manufacturing process flow.

Sustainable manufacturing system design considers both environmental and economic performance. Environmental management and sustainable models are increasing business priorities. So far, there are several methods for assessing the environmental impact of a company or the whole supply chain. Greenhouse gases, mainly carbon dioxide (CO_2), are released to the atmosphere directly when electricity is produced in situ and indirectly when it is provided from a grid due to the fossil fuel combustion. Also, the growing price of energy is another factor that needs to be taken into account during the manufacturing design phase. Equipment with a higher level of technology, i.e. more energy efficient, can produce less direct operating costs (Heilala et al., 2008).

2.2.4. Sustainable Manufacturing Process Concepts

A manufacturing process is deemed as a group of activities that converts inputs (raw materials, energy, etc.) into outputs (emissions, wastes and goods). In the traditional manufacturing processes, raw material, water, chemicals and energy - which input the process - are employed one time and leave the process as waste and products as shown in Figure 2.14.

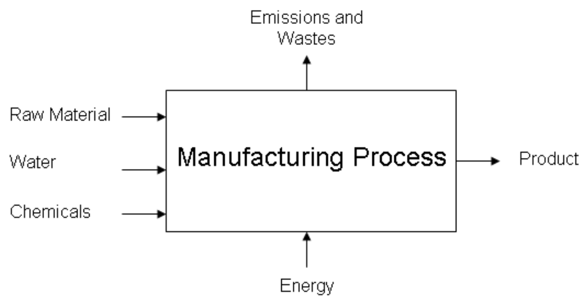

Figure 2.14 Traditional manufacturing process.

Some more advanced processes, such as: partly-closed and closed, can be found in the public domain (Beamon, 2008). In the partly-closed manufacturing process, raw material, water, chemicals and energy input the process and a portion of the process outputs are reused as inputs leading to a limited amount of waste (see Figure 2.15).

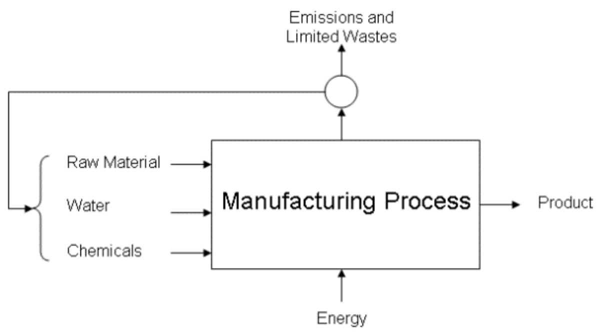

Figure 2.15 Partly-closed manufacturing process.

In the case of the closed manufacturing process, all the outputs generated are used as inputs for the same manufacturing process or another one causing no waste production (see Figure 2.16). An example of this type of manufacturing process is given by Inman (2006): All of Subaru of Indiana (SIA)'s waste are recycled, reused or burned to create energy. These two last manufacturing processes are becoming increasingly common in future manufacturing industries.

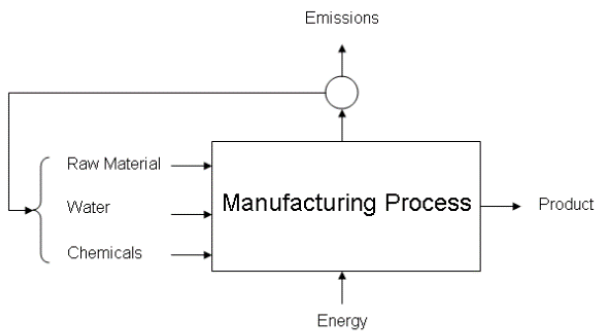

Figure 2.16 Closed manufacturing process.

2.2.5. Simulation Frameworks

Decisions in engineering and management need to take into account various variables and factors which are related to each other. In addition, the structure of the systems is so complex that it is difficult for human reasoning to deal with as a whole. Therefore, simulation modelling needs to be applied.

Manufacturing simulation and CAD/CAE tools have been used by the manufacturing industry. Nonetheless, in the case of sustainable manufacturing system design, different variables need to be optimised at the same time. The stakeholders involved in conceiving the manufacturing system require decision support to avoid a loss of performance.

There are many approaches and simulation tools which can be used during the manufacturing design phase. A simulation of a company, discrete event and material flow is employed to assess concepts and optimise them in order to find zones of concern and quantify and optimise manufacturing system operation (Heilala et al., 2008).

Today production atmospheres need standard efficient frameworks to simulate manufacturing processes. In a generalised reference model it is essential to emphasise the discrepancies and similarities between manufacturing systems resources, thus checking the opportunities of those concepts and their roles. The Optimizing Production Using Simulation (OPUS) project is a new computational language applicable to manufacturing systems with the help of an optimisation capability. A Business Process Modelling Notation (BPMN) approach has been used to create a framework associated with processes developed in business and the generalisation of the execution of the simulation tool (Battista et al., 2011).

Manufacturing systems are complicated and expensive. Simulation techniques have been adopted as an examination and assessment technique in the model and process of the systems. Popularity and widespread usage of computational models in the industry has led to a growth in the amount of simulation packages available (Hlupic and Paul, 1999).

Simulation simplifies the conception and production of manufacturing systems. The growth in competition in the industry has created a strong need for the computerised automated manufacturing systems. The use of these systems allows manufactures to achieve higher quality, with a lower cost; furthermore, flexibility in the design process allow for rapid improvements where necessary.

Due to the complicated, dynamic and stochastic performance of the system like this, simulation seems to be the correct method for modelling and examining innovative manufacturing systems. Moreover, it is possible to visualise the facility in an interactive way to get a good understanding and has resulted in a big utilisation of simulation in managing manufacturing issues.

The wider acceptance and realisation of the potential benefits of simulation technology by manufacturing industry has led to the release of a large quantity of simulators and computational languages for commercialisation (Hlupic and Paul, 1999). The features of the simulation software depend on the function of its work. The choice of the package by industry has two parts: one directing software range for quick modelling and second for specified modelling.

It is possible to classify simulation packages by simulation languages or as simulators (Law and Kelton, 1991). If a computational language is utilised, the model is created by means of writing routines with a modelling of a language. This method is flexible but expensive and takes time. A few of those programs are as follows: SIMAN (Pedgen et al., 1990), SLAM II (Pritsker, 1986), SIMSCRIPT II.5 (Russell, 1983), GPSS/H (Schriber, 1990), PCModel (White, 1988) and ECSL (Clementson, 1991).

Moreover, a simulator permits to model a particular system with no programming experience. Applying this method the computational effort is particularly diminished, and it is in this case that the system to analyse matches the domain of the simulator. For example: WITNESS (Anon, 1991), SIMFACTORY II.5 (Anon, 1992), XCELL+ (Conway et al., 1988), ProModelPC (Anon, 1991) and AutoMod II (Thompson, 1989).

The assessment and choice of the correct simulation software is the core of much research. Pidd (1989) gave a broad guidance regarding the selection of software based on discrete models, highlighting that the possible clients need to pay attention to sellers saying that the software can be used by both qualified statisticians and people who look at the world as being deterministic.

According to Bovone et al. (1989), who suggested a technique to assess the simulation software, they recommend some principles to be utilised for package assessment taking into account the following criteria: simplicity, flexibility, depurate, transportability, reliability and modelling and execution speed.

The selection of the software for the industry depends on the reason for modelling, and can be classified into two main categories. The first depends on the hierarchy of criteria for the selection with rapid modelling and the second hierarchy on criteria for detailed modelling with difficult real life manufacturing situations.

Rapid Modelling. In this case, the users are supposed to have dealt with computational modelling before and the procedural matters are known. Therefore, the manufacturing situation can be simulated quickly providing an overall picture and general data about the system.

The criteria to be considered would be as follows: support to build models, reduction in model development time, and typical components and execution measurements concerning manufacturing systems.

Detailed/Complex Modelling. In order to develop a detailed model of complex manufacturing systems, the most important criteria to consider when a simulation study is carried out are those symbolising the robustness package, less computational time and flexibility. The users are expected to have the experience and knowledge in computational models.

A sustainability framework was developed in Excel Microsoft by the US organisation called National Council for Advanced Manufacturing (NACFAM), which is an industry-led, policy research organisation located in the United States of America, to help manufacturing industry assess both economic and environmental factors of manufacturing processes using a few inputs (NAFCAM, 2010a). This platform is available for free in the public domain so that all manufacturers and the academia may have access to it and use it.

2.3 Energy Sources

During the last two centuries, the energy used comes from the earth. During the 1700´s most of the energy was obtained by means of firewood, water, wind and the effort of human/animal muscles. The main source of these types of energies was the Sun as it brought rain and wind, fed the trees and crops leading to the survival of living creatures. Due to the natural behaviour of these energies, they were renewable (Anon., 2014). Renewables utilise energy supplies which are restored naturally: sun, wind, water, heat emitted by the planet and vegetation. Technologies related to renewables change these energies into electric power, chemicals, heat and mechanical drive (Anon., 2001).

Roughly in 1800, some of the energy obtained came from coal. Then, by 1900 the energy generated had come from natural gas and oil sources. Before 1950, these resources mostly substituted the other kind of energy excluding the power of water. These fuels originate from decomposing residues of early animals and plants, therefore their energy source is the Sun as well. Nevertheless, this energy, stored during a long period of time in just some years, is being consumed.

Following 1950, the era of the atomic energy commenced using uranium. This element is not considered a fossil fuel and its energy source is not the sun. However, it is an exhaustible resource as is the case of fossil fuels.

In the last 25 years, the use of renewable energy has become more common since people have recognised that fossil and nuclear fuels are reaching their limit and are contaminating the environment. This energy, whose source is the sun in either way, offers prospects for an unrestrained energy source friendly with the environment.

As aforementioned, all types of renewable energy arises from the sun. It is possible to use direct sunlight e.g. solar heating systems, or indirect e.g. wind and hydroelectric power, and biomass. Renewable energy sources can be depleted if it is used faster than they can be reproduced. For instance, in England most of the forests were chopped for use as an energy source prior to coal appearance. If the resources are used prudently renewable energy can remain endless.

Currently, humanity's energy requirements are met using fossil fuels which are being depleted. Nuclear capacity in the USA will be finished by 2020 while the energy requirements will grow by 33%. A solution could be renewable energy (Anon., 2014).

Even if the amounts of conventional fuels were infinite the use of renewables brings benefits to the ecosystem. Frequently, the renewables are called green technologies since they emit little or no-greenhouse gas. The burning of fossil fuels releases gases into the air, which in turn retain the heat coming from the sun and promote climate change. Due to this situation, the temperature of the earth has increased; if this trend continues it will cause a rise in the level of the oceans, floods, heat waves, droughts and other severe conditions. Furthermore, by means of burning fossil fuels many pollutants are released into the air, water and soil. Air pollution leads to respiratory diseases, acid rain from nitrogen oxides and sulphur dioxide are harmful to fish and vegetation.

There are more options to the traditional energy sources as for example so-called alternative energy. They manage the energy in a more efficient manner helping energy sources to be more durable and to allow humanity extra time before fossil and nuclear fuels are exhausted. Using this type of energy leads to more sustainable systems for future generations.

2.3.1. Categories of Alternative and Renewable Energy

Nowadays, some sources of renewable are being used. A short description is given as follows (Anon., 2014):

- Hydroelectric power is one of the oldest and larger supplies of energy. It represents around 10% of the electricity used in the USA. The current hydropower capacity is

80,000 MW. Running water energy is transformed into electricity in the hydropower plants; basically the rivers are dammed to form reservoirs and then the water is released through hydraulic turbines generating electricity. This is a non-pollutant source of energy but the method of damming a river produces a big environmental impact on quality of water, fish and natural habitat.

- Biomass is the second largest source of renewable energy after hydropower. It has a capacity of 7,000 MW. Basically matter derived from wood, bark, and agricultural and industrial waste. This matter might be incinerated in power stations, specifically built for this purpose, and also can substitute even 15% of coal used as fuel in normal conditions. The burning of biomass produces less emissions of sulphur dioxide (SO_2) in comparison to the coal burning. Furthermore, methane gas can be obtained from biomass by means of gasification process. The energy produced by methane combustion in a boiler generates steam which turns steam turbines or in a combustion chamber in a gas turbine or reciprocating engine.
- Geothermal: in the USA geothermal energy capacity is more than 3,000 MW. These power stations employ underground high temperatures to generate steam; and then drive steam turbines to generate electricity. These stations can pump hot water using compressors from underground deposits or can warm water by means of forcing it to hot rock. It is possible to access the high underground temperatures by deep drilling. To some extent, this sort of energy is not renewable because at some point the core of the earth will be cool; but as this will happen in a long time, then it is considered as renewable.
- Solar Energy: this type of energy is applied to generate electricity, heat and for light. This energy is only a small part of the market in the USA. Solar energy can

be obtained in electrical power stations by means of solar heat or photovoltaic technology (more suitable for home use), which transform sunlight into electricity via solar cells. Sun heated systems are in two forms: active or passive. The active systems operate as follows: liquid or air flows throughout a series of solar collectors so that the heat can be carried where it is needed. On the other hand, passive systems refer to buildings with surfaces and windows placed in such a way that they maximise the absorption of the heat during winter. The latter are the most used.

- Wind Energy: according to (Anon., 2014) the installed capacity of this energy is 4,700 MW in the USA. This kind of energy is generated by the wind which rotates a group of blades fitted to a centre. This centre is attached to a shaft which drives an electric generator.
- Fuel Cells are an alternative but not necessarily a renewable energy device; they can be called renewable if the fuel employed in this device is renewable. This electrochemical device transforms the energy of a chemical reaction into heat and electrical power. On contrary to a battery, a fuel cell has the ability of producing power until the fuel provided to them is exhausted. Nowadays, fuel cells are manufactured using hydrogen and oxygen.
- Hydrogen is high in energy producing water as the only emission. Today's industry generates hydrogen in amount of more than four trillion cubic feet per year. The hydrogen fuel cells present a big capability to generate electrical power for both vehicles and distributed systems. Researchers are trying to generate hydrogen directly from water by means of biomass, wind and solar energy (Anon., 2014).

- The ocean produces two types of energy: thermal from the sun heat and mechanical from waves and tides. Thermal energy from the ocean can be used for generation of electricity; systems of electric power conversion using surface sea water to spin a turbine that activates a generator; this involves mechanical devices (Anon., 2014).

2.4 Colombian Aluminium Sector

Aluminium is a metallic chemical element; pure aluminium has little strength and ductile characteristics; however it can form alloys with various elements to improve its strength as well as to acquire several useful properties. Aluminium alloys are lightweight, strong, and easy for making many metalworking processes; they are easy to assemble, machine or cast, and they are suitable for several finishes due to its properties; aluminium is the most non-ferrous metal employed in different sectors.

Aluminium is air-stable and not affected by corrosion from sea water, liquid solutions and many several chemicals due to an impenetrable oxide layer which keeps it out of corrosion. With purity of 99.95%, aluminium is resistant to most acids, but is dissolved in water. Its oxide layer is dissolved in alkaline solution and the corrosion is rapid.

Aluminium provides an excellent mixture of properties, low weight, high strength, excellent formability, excellent electrical and thermal conductivity, smart surface finish, high corrosion resistance; these properties allow their use in almost all kinds of designs and product applications as well as low recycling cost and a long useful life.

Its application in construction represents the largest market for aluminium industry. Thousands of homes have used aluminium doors, locks, windows, screens, nozzles and drainage channels. Aluminium is also one of the most important products in the industrial construction. The transport market is in the second position. Several military and commercial aircraft are made almost entirely of aluminium. With respect to the car industry, aluminium appears as rims, inner and outer edges, air conditioners, grills, engine cooling and automatic gearboxes, car body panels and cylinder blocks. It is also used in bodies, rail wagons, structures of high-velocity cars, formed wheels for trucks, cars, cargo containers and road signs, lanes and lighting division.

In the aerospace industry, aluminium is also found in aircraft engines, structures and landing gears, covers and interiors; often close to 80% of the weight of the aircraft is aluminium. Further, the companies dedicated to food packaging are rapidly growing. Wires and aluminium cables are the main goods in electrical appliances. It is possible to find it at home in the form of kitchen utensils, foil, tools, portable appliances, air conditioners, freezers, refrigerators, and sports kits for example tennis rackets and skis. There are many chemical applications suitable for aluminium and its substances. Aluminium powder is employed in explosives and fuel for rockets, paints and also as a reducing agent.

The Alumina Group SA is a leader in the Aluminium industry in Colombia and is known internationally as an active company, which sells aluminium extruded items. The Empresa MetalMecánica de Aluminio S.A. (EMMA) Metalworking Company, located in the town of Itagüi in Antioquia (Colombia), is dedicated to the process of extrusion, anodised and paint of aluminium as described below.

Recyclable Material. Aluminium recycling is a process where aluminium waste can be converted into other products after its primary utility. This process involves simply metal recast, which is much cheaper and consumes much less energy than producing aluminium from the electrolysis of alumina (Al_2O_3). Recycling aluminium needs just 5% of the energy consumed to process aluminium of the mine.

Recyclable aluminium collected at the EMMA plant is provided by different sources such as used pots, kitchen cutlery, beverage cans, industrial tools, rods, auto parts, bicycles, computers, off-cuts or discarded profiles, among others (see the figure below).

Figure 2.17 Recyclable aluminium collected at the EMMA plant.

This material is organised and pressed which is called Secondary Aluminium so that it can be sent to the company “Alumina” located in the city of Cali where it is melted and the ingots - which are used for the extrusion - are made. Pressing process is performed in the city of Cali due to reduced costs not only generated by the transport but the cheaper gas price in that city.

Ingots. The aluminium alloy intended for extrusion is formed into large cylindrical ingots called billets which are produced by casting; they have a length of 6 meters, a diameter of about 300 mm and a mass of approximately 500 kg each (see

Figure 2.18). These billets are cut to a certain size in order to optimise the extrusion that is carried out at all times; then they are organised and loaded to be homogenised.

Figure 2.18 Aluminium billets.

Homogenisation. The initial heat treatment applied to the ingots before secondary operation such as hot rolling is the homogenisation. Homogenisation has one or more purposes depending on the alloy and the product. One of the main purposes is to reduce the harmful effects of micro-structural features existing on structures or casting solidification (refer to Figure 2.19).

Injection – Extrusion. After aluminium is homogenised, ingots are loaded into the Oven of the Injection Machine to be transformed into useful products for industry, where by pressure the matrix (located at the top of the oven) is filled to get the aluminium shapes required; in this stage of the process, injection time and cooling time are verified through a visual inspection of the semi-elaborate piece, which is organised in a conveyor belt.

Extrusion is the process that transforms aluminium into useful products for industry, by allowing the adaptation of aluminium to practically all industries, products and environments. Extrusion consists of moving the preheated aluminium at high pressure through a matrix whose opening corresponds to the cross section of the extrusion profile; thus the basic elements of the extrusion are the aluminium matrix, the press and its auxiliaries, and extrusion parameters. The matrices are made of high temperature resistant steel, and its opening is performed by computer-controlled EDM (Electrical Discharge Machining).

Figure 2.19 Aluminium homogenisation.

It is important to point out that there are dimensional limits in the extrusion of profiles. These limits vary depending on the hardness of the alloy used and affect the thickness, radii and minimum angles that are possible to extrude. Such controls and adjustments are made periodically during the lifetime of the matrix. The most common applications are aluminium profiles for windows and doors, lighting, railings and furniture. This material is highly suitable for anodising - both decorative and protection purposes. Extrusion presses are hydraulic machines that consist of a container where the billet is placed, a matrix holder and a plunger to apply pressure (see Figure 2.20).

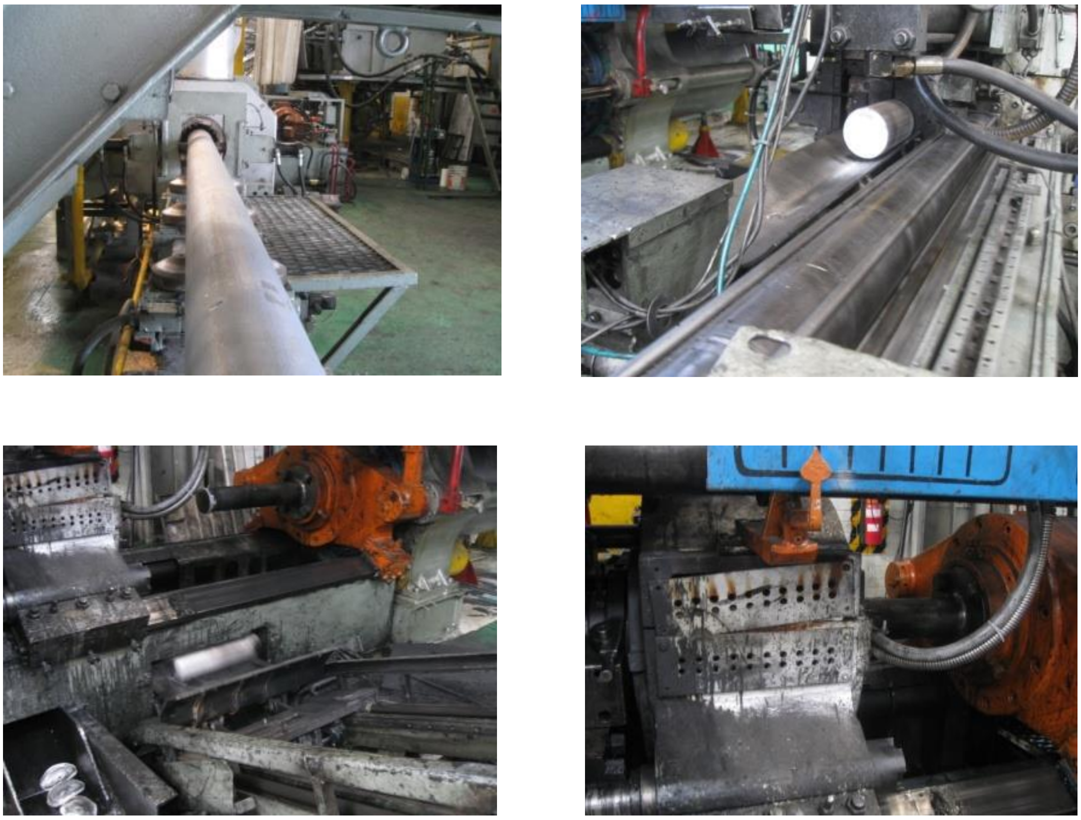

Figure 2.20 Aluminium injection and extrusion.

The already cooled profiles placed at the end of the work table and storage of the press whose length usually vary between 48 and 55 meters, are then subjected to a small stretch to eliminate any stress in the material and straighten the slight curvatures that could be in the extruded bars (see Figure 2.21). The bars are cut, by a saw placed at the end of the table, into commercial lengths, between 4 and 7 meters, and are subsequently deposited in containers and finally introduced into an aging furnace at 175 °C for a period of about 4 hours.

Figure 2.21 Aluminium extrusion and profile location.

***Painting: Electrostatic Painting*.** The paint process consists of a type of layer which is put on as a dry powder fluid that usually is employed to make a hard finish. The process is carried out in facilities equipped with a curing oven, booths for the application with electrostatic guns and a chain where the parts are hung. Excellent results are expected in terms of finish and airtight sealing, with colours it is possible to obtain all the nuances; also, it is easier to apply and from the ecological point of view, does not create any problems for operators and the environment (see Figure 2.22).

Figure 2.22 Painting process.

Anodising. Anodised aluminium is a kind of aluminium that, after a certain electrolytic treatment, is coated with a layer that provides greater protection from environmental threats. The term anodised for this type of protection treatment, comes from the word anode. An anode is a positive pole of an electrolyte. This procedure is particularly done, because aluminium is oxidised very quickly with contact with oxygen. This oxide layer is not strong enough to withstand high amounts of moisture or exposure to other factors such as industrial smoke and sea salt (see Figure 2.23).

The anodising process essentially consists of immersing the aluminium in an acidic solution, generally, made of sulphuric acid. Later, thanks to the application of a current, a release of oxygen - whose thickness depends on the time that has been exposed to the solution – is produced. To complete the process, aluminium is submerged in hot water to close the pores of the surface. From the above process, the oxide layer covering the aluminium comes from itself, allowing it to be an integrated piece. Once all these stages are finished this may be called "aluminium", anodised aluminium. As mentioned before, the purpose of this electrolytic process is to cover the piece of aluminium with a protective layer which - due to oxygen - consists of aluminium oxide. This layer is transparent, hard and resistant to different factors present in the corrosive environment.

Among the advantages of anodising, high resistance to abrasion and contact with abrasive cleaners are found, allowing the treated parts to be much more resistant. Moreover, thanks to the oxide layer that is integrated into the aluminium, it does not suffer scratches or peeling, also is not affected by exposure to sunlight.

Figure 2.23 Anodising process.

2.5 Summary

There is strong evidence that our planet is running out of natural resources of raw material and energy which is leading to an increase in their price and limitation. The energy used to power our societies is mainly based upon fossil fuels. Firstly, the global oil production is approaching its maximum value; secondly, its residual sources are more limited and found in areas which are unstable politically.

Furthermore, there is increasing indication that climate change is happening. The global warming and ozone layer depletion are the consequences of the activities of many countries. Acid rain, which is contaminating the water available on the earth (e.g. rivers and lakes) and destroying forests, often originates in one country and is placed in another. Consequently, there are more stringent regulations to come which will have an impact on the way the economy is run. In other words, it will demand that businesses are more responsible for environmental damage and be more proactive to mitigate their environmental impact.

Taking into account the above, there will be more pressure on the manufacturing industries to generate the required water, foods, services and products to maintain the earth's population with less environmental impact. Metal products constitute a large proportion of manufactured products and large amounts of energy are consumed typically in their manufacture, and the behaviour of the metallurgy and metalworking sector reported an important growth in the world. Besides, aluminium is a priority in the metal sector since it is the non-ferrous material more common on the earth and is used for many applications ranging from building to aerospace industry.

Several sustainable manufacturing process concepts are found in the literature as follows:

- Traditional process i.e. raw material, water, chemicals and energy which are inputs of the process, then employed during the process and leaving it as products, emissions and residual waste, and

- partly-closed and/or closed process i.e. raw material, water, chemicals and energy input to the process or a portion of the process and all of its outputs are recycled leading to a limited amount of waste, for minimal environmental and economic impact.

Additionally, the renewable energy usage during the manufacturing process can reduce the environmental impact making the process more sustainable.

CHAPTER 3

MULTIDISCIPLINARY SIMULATION FRAMEWORK

3.1 Overview

In order to answer the research questions a multidisciplinary simulation framework or tool needs to be used. This tool will have to be made up of various modules which can assess the environmental and economic performance for different manufacturing processes (see Figure 3.1) which is the case for NACFAM Sustainability Framework Model available to the public. The metal i.e. aluminium, products are chosen since they dominate the engineering manufacturing sector. In addition, the processes will be assumed to have one specific product with the same quantity. The validation of the model will use available data in the public domain and the scenarios to be assessed will use the aluminium-product industry.

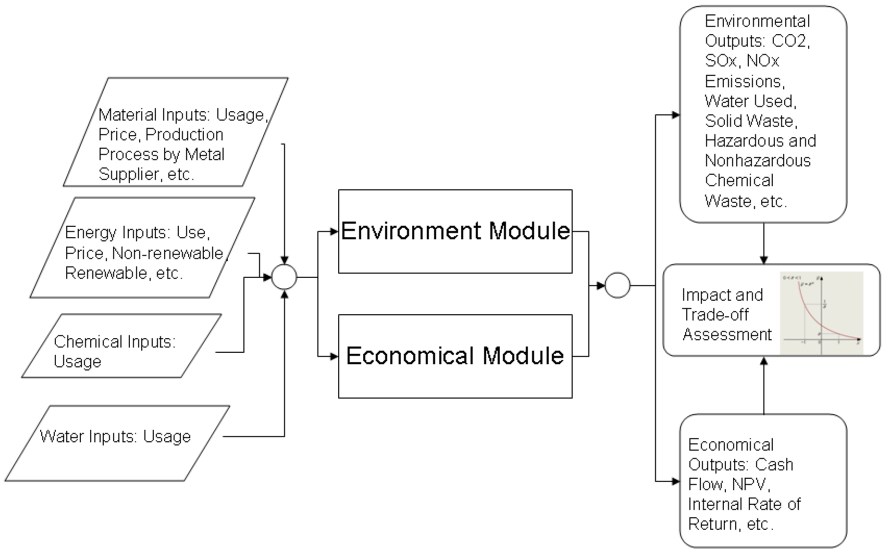

Figure 3.1 Multidisciplinary simulation framework.

3.1.1 NACFAM Sustainability Framework Model

This model was created to assist companies in looking at sustainability from a more holistic standpoint (NAFCAM, 2010a). This contains an economic module to calculate the financial performance of a project or a group of projects and an environmental module for emissions and waste performance. In summary, this model can be used for analysing the environmental and economic impacts for both a single project and various projects at the same time and in combination. It was developed in Microsoft Excel because all manufacturers have access to it and already use it (see Figure 3.2).

Figure 3.2 Inputs and outputs for NACFAM Sustainability Framework Model. Source: NAFCAM (2010a).

People in any level of the company can use this model in the following stages:

- Manufacturing Product Design
  - Products must be designed taking into account their entire life cycle.

- When a product is designed it is necessary to consider its production, raw material, effect of materials utilised, product end life and its life cycle performance.

- Strategy Development for a Manufacturing Process

- The effectiveness of a company depends on sustainable manufacturing processes.

- This framework makes the manufacturing process more sustainable and lucrative.

- It is necessary to use estimated data to rank possible sustainable manufacturing assignments.

- Manufacturing Implementation

- This framework offers data at each step of sustainable manufacturing implementation to guarantee sustainability.

- This framework can be used when the company has good information on selected tasks to have more specific estimations for economic and environmental performance to facilitate project assessment and use these data for next tasks.

- Strategy Development

- To really inform people about the company strategy and the interaction between finances and environment in a holistic way.

- To develop the environmental strategy of the company.

NACFAM sustainability framework can be used when:

- evaluating the environmental and economic impacts in a project,

- evaluating the environmental and economic effects for many projects at the same time and in groups and

- considering many projects the framework can be turned on and off for every single project to evaluate the collective effect of several arrangements of projects.

This simulation framework can be employed either as a preliminary tactical tool to create the company strategy for sustainability or as an advanced tool for several project options in further detail. It is essential to start running this framework with educated guesses or limited data at the beginning to assist the company in establishing its sustainability strategy and priorities. Frequently guesses are sufficient to see where opportunities are placed.

Regarding the inputs required to run the model three levels are found: the first level consists of general inputs and assumptions such as category of factors related to emissions of greenhouse gases, discount and tax rates. The next level is the inputs for manufacturing processes i.e. the usage and the price for raw materials, chemicals, energy, waste and water regarding the baseline for a specific facility or a company. The third level is associated with a specific project: a process, new against old machinery or other change expected to be assessed.

The simulation framework calculates both environmental and economic indicators. Its aim is to give an illustration of how several project alternatives, strategies and machinery reduce costs against their environmental impact. The framework uses economic factors - like discounted cash flows (DCFs) – to figure out how variations during manufacturing processes can affect the cash flow on a discounted basis, and environmental factors to calculate the emissions produced by these variations.

It is possible to determine the year where the project starts to pay back by just checking the discounted cash flow and see in which year that flow becomes positive (i.e. Payback Period). The internal rate of return (IRR) can be calculated for economic analysis. Another financial figure found in this simulation framework is the net present value (NPV).

Some of the environmental metrics given by the framework are: greenhouse gas emissions (CO_2eq, carbon dioxide equivalent), sulphur oxides emissions (SO_2eq, sulphur dioxide equivalents), nitrogen oxides emissions, solid, hazardous and non-hazardous chemical wastes, among others.

3.2 Validation and Verification (v/v)

After a detailed search in the open literature three papers were selected which seem to have representative data (i.e. inputs and outputs) to validate/verify the baseline computational model.

One of the reports under the title of "Life Cycle Impact Assessment of Aluminium Beverage Cans", prepared for Aluminum Association, Inc. Washington, D.C. by PE Americas is applicable to Life Cycle Assessment (LCA) for aluminium cans, has the necessary data suitable for the model v/v. However, these data are incomplete due to the confidentiality of the project which makes it very hard to run the v/v process. Another report developed by European Aluminium Association, named ”Environmental Profile Report for the European Aluminium Industry”, contains data relevant only to aluminium raw material production. Therefore, the data provided in this report is unsuitable for the model validation/verification (v/v). Finally, a case study (i.e. an example) provided by the National Council for Advanced Manufacturing (NACFAM) is found suitable to verify the computational model as most of the data are given (NACFAM, 2010b). As a result, a discrepancy of 0% for both economic and environmental performance was obtained; this is shown in the table below. I would like to highlight that this case study is very similar to the baseline scenario of this research. The reliability of these data cannot be guaranteed.

Table 3.1 Validation and verification results.

	Simulation	Public Data	Deviation (%)
Carbon Dioxide (CO_2) [tonnes] p.a.	2,291.01	2,291.01	0.00
Sulphur Oxide (SO_x) [tonnes] p.a.	15.58	15.58	0.00
Nitrous Oxide (NO_x) [tonnes] p.a.	3.26	3.26	0.00
Net Present Value (NPV) [US$] for 10 years	0.00	0.00	0.00

3.3 Design of Experiments (DOE)

The DOE are a gathering of statistical approaches giving a systematic and useful manner to explore a design space (Montgomery, 1996). These techniques are very efficient when dealing with unknown design spaces leading to important data about them – design space decrease. Furthermore, the DOE can be used to assess the impact of several input variables on one or more output responses. This is known as key drivers' identification.

There are different DOE methods available in the public domain. A broad explanation of them and their application to solve engineering design problems is presented by Simpson et al (1997). For this study three techniques were considered as follows: full factorial, parametric study and Taguchi (orthogonal arrays). The full-factorial technique analyses the responses of the outputs at all possible combination of input variables once the levels (values) for every factor (variable) have been established. In the case of parametric study, one factor has to be changed at a time while the remaining is left unchanged. Finally, Taguchi's technique (Taguchi and Konishi, 1987) is applied to achieve the characteristics of a design space established on a small quantity of data points.

Both parametric study and full-factorial methods are very expensive in computational time. In other words, many experiments need to be run to obtain an analysis. As a consequence, the Taguchi's orthogonal arrays were used due to less computational time involved in this technique. The experiments were run using a computational program available commercially called Minitab 16 (user's manual, 2010). The input variables chosen for this DOE are as follows: 1) average annual electricity use, 2) electricity price, 3) average annual gas use, 4) natural gas price, 5) average annual water use, 6) price of water, 7) price of material, 8) chemical usage, 9) price of chemicals, 10) solid waste, 11) hazardous waste, 12) non-hazardous waste whilst the responses for environmental performance are: 1) SO_x, 2) CO_2 and 3) NO_x, and for economic performance is 1) net present value (NPV). The outcome of this study is explained as follows:

- As depicted in Figure 3.3, the input variable with a key impact on SO_x production during the design process of aluminium cans is the electricity use. This is because 100% of electricity is provided by a grid in the state of Pennsylvania – according to the simulation - where the majority of the electricity is generated using coal which is one of the contributors to SO_x emissions.

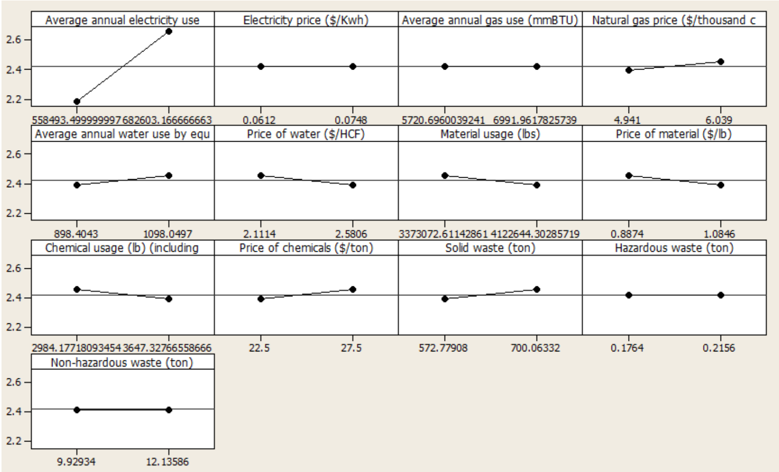

Figure 3.3 DOE for SO_x impact using Taguchi's orthogonal arrays.

- In Figure 3.4 the responses of CO_2 from input variables are shown. Both electricity and natural gas usage have a significant impact on CO_2 emissions. Coal is one of the biggest anthropogenic of carbon dioxide discharges on the planet. Furthermore, the combustion of natural gas generates CO_2 emissions although to a lesser extent than for coal burning.

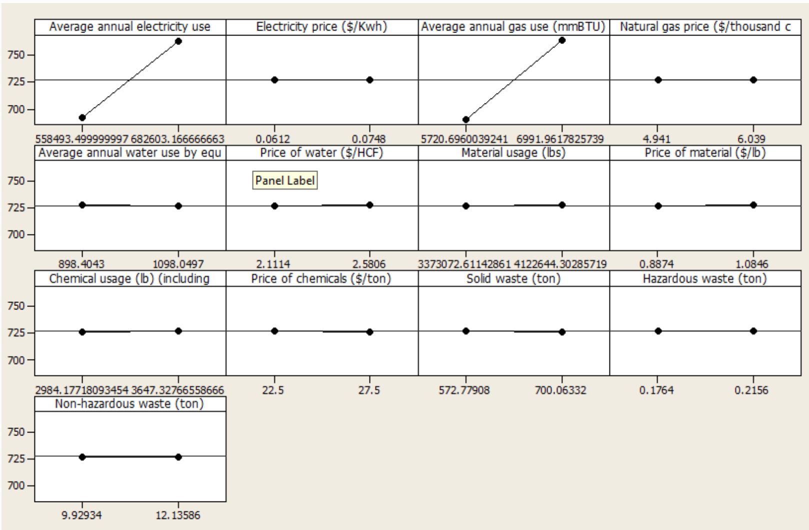

Figure 3.4 DOE for CO_2 impact using Taguchi's orthogonal arrays.

- Figure 3.5 portrays the effect of several input variables on the production of NO_x. The explanation is given above in the case of CO_2 releases.

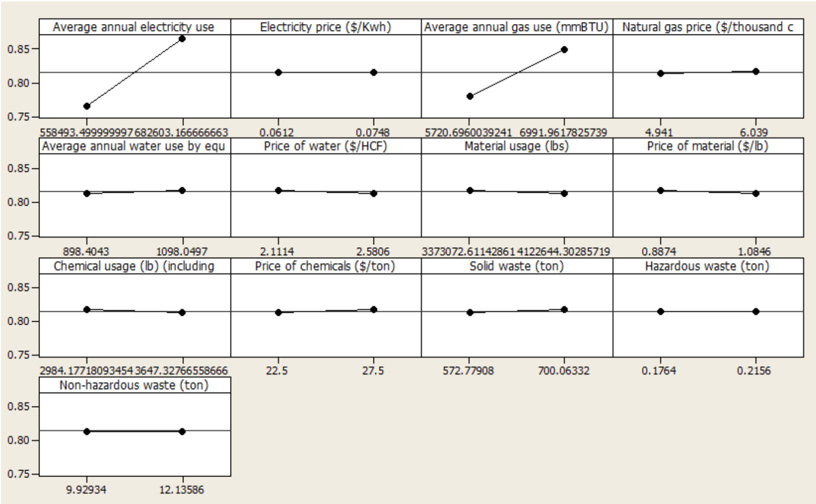

Figure 3.5 DOE for NO_x impact using Taguchi's orthogonal arrays.

- Figure 3.6 indicates that the price of material has an important impact on the NPV since it is embedded in the direct operating cost. The NPV is made up of both incoming and outgoing cash flows for a period of time, i.e. 10 years.

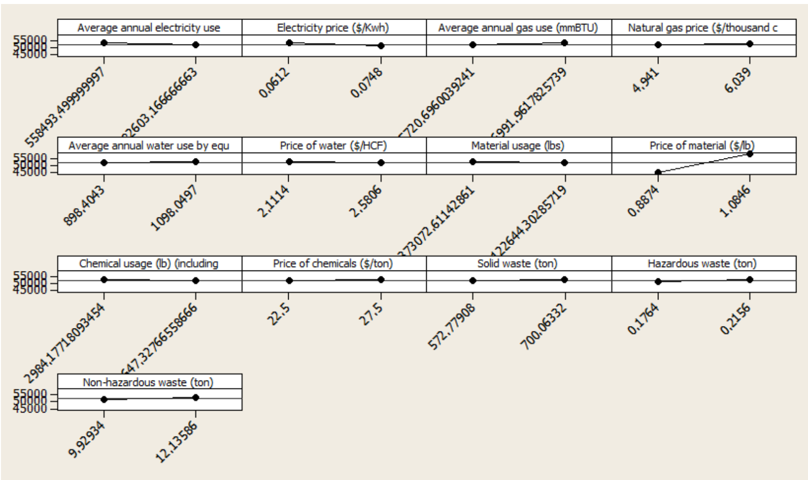

Figure 3.6 DOE for NPV impact using Taguchi's orthogonal arrays.

3.4 Summary

A sustainability assessment framework available to the public domain was used to address the research questions of this thesis. This framework is called "Sustainability Framework Model" and was created by National Council for Advanced Manufacturing (NACFAM) which is made up of: environment and financial modules.

In order to identity the relevant inputs, the Taguchi's orthogonal arrays were used in a computational package called "Minitab 16". The reason for this is that it involves less computational time. As a result, the input variables identified by the Design of Experiments run are the following: average annual electricity use, average annual gas use and material price. These variables have influences on environmental performance (SO_x, CO_2 and NO_x) as well as on economic performance (Net Present Value).

If the reader would like to replicate the above-mentioned methodology, then the following steps need to be performed: firstly, identify the needs in the manufacturing sector under study. Secondly, determine the requirements and the architecture of the simulation framework to assess the economic and the environmental sustainability of the traditional or non-traditional manufacturing processes. After that, identify the existing computational models in order to simulate the different disciplines involved in a particular study. And then, define the scenarios (i.e. manufacturing processes) to be assessed. Carry out the validation-verification process for the scenarios under investigation. Afterwards, identify the key drivers of the manufacturing processes by means of design of experiments (DOE). Finally, assess the economic cost and environmental impact of the scenarios defined previously. Based on assessments, make the decisions supported by the requirements.

CHAPTER 4

RESULTS AND DISCUSSION: CASE STUDIES

4.1 Problem Formulation

The baseline and sustainable scenarios are defined taking into account the following assumptions:

- The final metallic product (aluminium cans) will be constant (i.e. the same in dimensions and quantity) in order to have a fair comparison.
- Regarding the Life Cycle Assessment (LCA), the environmental performance during metal production process (upstream) will be assessed. No downstream will be analysed due to the time limitation of this project. This could become future work for other studies.
- All the case studies will be evaluated at conceptual design level, i.e. no detailed design level will be considered due to the timeframe of this project.

➢ **Scenario 1: Baseline**

Table 4.1 Inputs for baseline scenario.

Inputs	Values
Annual aluminium used [lbs]	80,000 *
Aluminium price [$/lb]	20 *
Electricity used by equipment monthly [kWh]	10,000 *

* These values are taken from NACFAM (2010b)

In Tables 4.1, 4.2, 4.3 and 4.4 the definition of baseline and sustainable manufacturing processes are shown as well as the schematic of each process (see Figures 4.1, 4.2, 4.3 and 4.4).

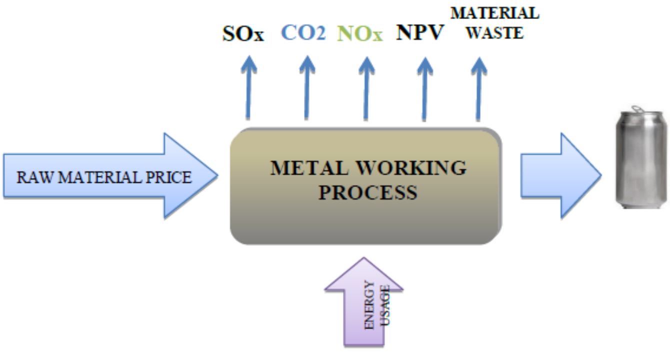

Figure 4.1 Baseline schematic.

- **Scenario 2: Implementation of new technology**

By using new technology i.e. new equipment, it is possible to decrease the material usage. However, the economic performance of the project will be affected due to the investment required to obtain such equipment. Inputs for scenario "implementation of new equipment."

Inputs	Values
Annual aluminium used [lbs]	15,996 *
Aluminium price [$/lb]	30 *
Electricity used by equipment monthly [kWh]	15,000 *
New equipment cost [US$]	600,000 *

* These values are taken from NACFAM (2010b)

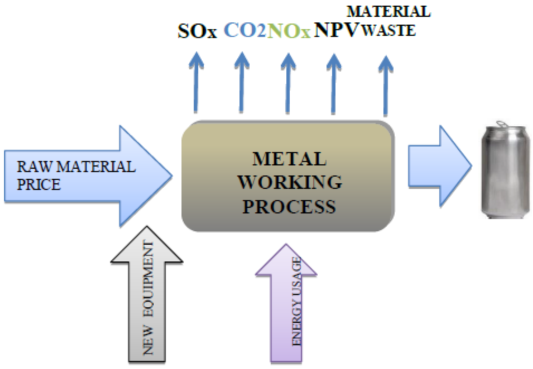

Figure 4.2 Schematic for implementation of new equipment.

- **Scenario 3: Reuse of material waste**

During the process of manufacturing aluminium cans many different sort of waste can be obtained. Due to environmental concern, it is necessary to find the way to reuse such waste. In this case, less amount of raw material needs to be obtained owing to the percentage of material that can be reused. As a result, the environmental performance upstream would be less due to less energy required to produce the raw material.

The aluminium waste is also called secondary aluminium ingot, which is obtained from post-consumer scrap; such waste can be retrieved from the recycling plants or individuals whose main way to get income is **recycling**.

Table 4.2 Inputs for scenario "reuse of material waste."

Inputs	Values
Annual aluminium used [lbs]	60,000 **
Aluminium price [$/lb]	20 *
Electricity used by equipment monthly [kWh]	10,000 *
Reuse waste [lbs]	20,000 **

* These values are taken from NACFAM (2010b)
** These values are taken from PE AMERICAS (2010)

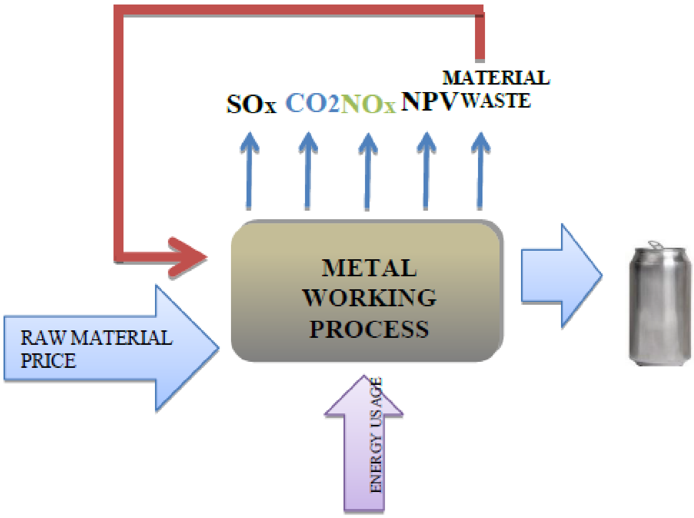

Figure 4.3 Schematic for reuse of material waste.

➢ **Scenario 4: Electricity provided by the grid and the renewables**

The baseline scenario uses energy only from the grid. In this case scenario, 95.54 % of the electricity is provided by the grid while 4.46 % by renewables (PE AMERICAS, 2010).

Table 4.3 Inputs for scenario "electricity provided by the grid and renewable."

Inputs	**Values**
Annual aluminium used [lbs]	80,000*
Aluminium price [$/lb]	20 *
Electricity used by equipment monthly [kWh]	10,000*
Electricity used from the grid [%]	95.54 **
Electricity used from renewables [%]	4.46 **

* These values are taken from NACFAM (2010b)
** These values are taken from PE AMERICAS (2010)

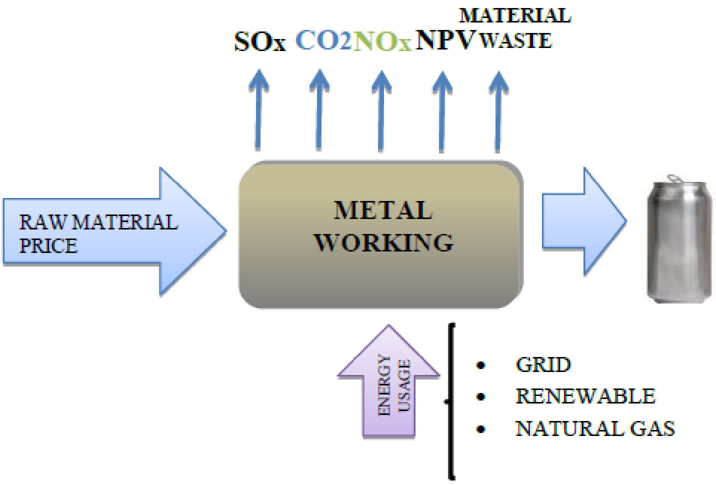

Figure 4.4 Schematic for use of renewable energy.

4.2 Case Studies

The four scenarios were described in the previous section and the simulations were performed using the sustainability analysis computational tool provided by the National Council for Advanced Manufacturing (NACFAM) obtaining the following outcomes:

➢ **Scenario 1: Baseline**

The outputs for baseline scenario are given below.

Table 4.4 Outputs for baseline scenario.

Outputs	Values
CO_2 emissions p.a. [tonnes]	2,291.01
SO_x emissions p.a. [tonnes]	15.58
NO_x emissions p.a. [tonnes]	3.26
Net Present Value for 10 years [US$]	0.00

Using 80,000 pounds of Aluminium which cost \$20/lbs and an equipment which uses 10,000 Kwh of electricity monthly leads to an amount of 2,291.01 tonnes of CO_2 per annum, 15.58 tonnes of SO_x per annum and 3.26 tonnes of NO_x per annum.

- **Scenario 2: Implementation of new technology**

Implementing new equipment and using data from the Table 4.2 (from the previous section) the following results were obtained:

Table 4.5 Outputs for scenario "implementation of a new equipment."

Outputs	**Values**
CO_2 emissions p.a. [tonnes]	2,325.28
SO_x emissions p.a. [tonnes]	15.82
NO_x emissions p.a. [tonnes]	3.31
Net Present Value for 10 years [US\$]	1,048,921.00

The new equipment processes 15,996 lbs of aluminium every year (it is very effective with respect to material usage); the aluminium price increases with respect to the baseline price due to commercial agreements (if the quantity purchased is less, then the sale price is going to be higher); and the new equipment consumes 15,000 Kwh with a price of \$600,000 invested in the first year of the project.

The results obtained were as follows: 2,325.28 tonnes of CO_2 p.a., 15.82 tonnes of SO_x p.a. and 3.31 tonnes of NO_x p.a. In the case of the Net Present Value (NPV), an amount of US\$1,048,921 was achieved for a total period of ten years corresponding to the time of project evaluation. The higher environmental impact in comparison to the baseline scenario is due to more electricity being required by the new equipment i.e. 15,000 kWh instead of 10,000 kWh for the baseline equipment. As shown in Table 4.7, the project is profitable due to the less raw material use but at the expense of the manufacturing environmental impact.

Table 4.6 Comparison between scenarios 1 and 2.

Outputs	Baseline	Scenario 2	Deviation (%)
Carbon Dioxide (CO_2) [tonnes] p.a.	2,291.01	2,325.28	1.50
Sulphur Oxide (SO_x) [tonnes] p.a.	15.58	15.82	1.54
Nitrous Oxide (NO_x) [tonnes] p.a.	3.26	3.31	1.49
Net Present Value (NPV) [US$] for 10 years	0.00	1,048,921.00	N/A

In terms of manufacturing process the environmental impact of scenario 2 is higher than that of baseline one (please refer to Table 4.7). This is because the new equipment is assumed to consume more energy than the baseline one i.e. 15,000 kWh rather than 10,000 kWh. Nevertheless, this new equipment is efficient when dealing with the raw material which results in less production cost leading to a better NPV.

On the other hand, the environmental impact upstream (i.e. material production) is less in comparison to the baseline. The emissions difference between both scenarios for a ten year period is as follows: - 7,168 tonnes for CO_2 and - 41.92 tonnes for SO_x. This can be explained through the fewer raw materials needed and the energy required to process it. In addition to that, a difference of NO_x for manufacturing process up to 10 years is 0.49 while the solid waste produced in obtaining the raw material gives a gap of - 1,440. Overall environmental impact i.e. putting together the emissions released during the material production and product manufacturing, of the scenario 2 is appealing (see difference value @ LC level given in Table 4.8). Its economic impact -

NPV - for the manufacturing process is attractive since it gives a 10 years profit of US$1,048,921.

Table 4.7 Comparison between scenarios 1 and 2 for a period of 10 years.

Scenario 2 vs Baseline	Environmental Impact for Manufacturing Process (Can Manufacturing)	Environmental Impact Upstream (Material Production)	Difference Value @LC
	Difference Value for 10 years		
Carbon Dioxide (CO_2) [tonnes]	343.65	-7,168.00	-6,824.35
Sulphur Oxide (SO_x) [tonnes]	2.34	-41.92	-39.58
Nitrous Oxide (NO_x) [tonnes]	0.49	N/A	0.49
Solid Waste Burden [tonnes]	N/A	-1,440.00	-1,440.00
Net Present Value (NPV) [US$]	1,048,921.00	N/A	1,048,921.00

- **Scenario 3: Reusing the material waste**

Reusing the material waste generated during the manufacturing process of aluminium cans and the data from Table 4.3 given in the previous section, the next results were obtained:

As observed from the results in Table 4.10, there is no emissions difference between the scenarios 3 and baseline as the equipment uses the same amount of energy as the baseline scenario. However, a profit of US$5,375,131 is possible for a period of 10 years due to the reuse of the material waste leading to a decrease of the raw material usage.

Table 4.8 Outputs for scenario "reuse of material waste."

Outputs	Values
CO_2 emissions p.a. [tonnes]	2,291.01
SO_x emissions p.a. [tonnes]	15.58
NO_x emissions p.a. [tonnes]	3.26
Net Present Value for 10 years [US$]	5,375,131.00

Table 4.9 Comparison between scenarios 1 and 3.

Outputs	Baseline	Scenario 3	Deviation (%)
Carbon Dioxide (CO_2) [tonnes] p.a.	2,291.01	2,291.01	0.00
Sulphur Oxide (SO_x) [tonnes] p.a.	15.58	15.58	0.00
Nitrous Oxide (NO_x) [tonnes] p.a.	3.26	3.26	0.00
Net Present Value (NPV) [US$] for 10 years	0.00	5,375,131.00	N/A

The environmental impact upstream, i.e. material production, is less due to the reduction of energy consumption for raw material production. This case reuses the solid waste generated during the product manufacturing process leading to less raw material acquisition. The difference in values between scenarios 3 and baseline for ten years timeframe is: -2,240 tonnes for CO_2 and -13.10 tonnes for SO_x (see Table 4.11).

Table 4.10 Comparison between scenarios 1 and 3 for a period of 10 years.

Scenario 3 vs Baseline	Environmental Impact for Manufacturing Process (Can Manufacturing)	Environmental Impact Upstream (Material Production)	Difference Value @LC
	Difference Value for 10 years		
Carbon Dioxide (CO_2) [tonnes]	0.00	-2,240.00	-2,240.00
Sulphur Oxide (SO_x) [tonnes]	0.00	-13.10	-13.10
Nitrous Oxide (NO_x) [tonnes]	0.00	N/A	0.00
Solid Waste Burden [tonnes]	N/A	-450.00	-450.00
Net Present Value (NPV) [US$]	5,375,131.00	N/A	5,375,131.00

- **Scenario 4: Electricity provided by the grid and the renewables**

With the possibility of use of electricity from renewable sources, scenario 4 was evaluated using the data from Table 4.4 in the previous section.

Using only 4.46% energy from renewable sources it was possible to see a difference regarding the emissions leading to a difference of 4.36% between the baseline scenario and scenario 3 in CO_2, 4.43% in SO_x and 4.34% in NO_x (refer to Table 4.13). The reason for this is that less electricity is taken from the grid which uses either coal-fired power plants or thermoelectric power plants - in turn they use fossil fuel to produce electrical power. The economic aspect is not attractive due to the implications in using in-situ renewables.

Table 4.11 Outputs for scenario "electricity provided by the grid and the renewable."

Outputs	Values
CO_2 emissions p.a. [tonnes]	2,188.83
SO_x emissions p.a. [tonnes]	14.89
NO_x emissions p.a. [tonnes]	3.12
Net Present Value for 10 years [US$]	0.00

Table 4.12 Comparison between scenarios 1 and 4.

Outputs	Baseline	Scenario 4	Deviation (%)
Carbon Dioxide (CO_2) [tonnes] p.a.	2,291.01	2,188.83	-4.46
Sulphur Oxide (SO_x) [tonnes] p.a.	15.58	14.89	-4.43
Nitrous Oxide (NO_x) [tonnes] p.a.	3.26	3.12	-4.34
Net Present Value (NPV) [US$] for 10 years	0.00	0.00	N/A

Using renewable energy the amount of emissions is less during the product manufacturing process because the electricity is provided by both the grid and the renewables leading to a decrease of CO_2, SO_x and NO_x emissions. The upstream environmental impact remains the same because the raw material production is constant (refers to Table 4.14). The NPV – an economic indicator of the product manufacturing process –remains the same as the baseline one due to the maintenance costs involved in renewables.

Table 4.13 Comparison between scenarios 1 and 4 for a period of 10 years.

Scenario 4 vs Baseline	Environmental Impact for Manufacturing Process (Can Manufacturing)	Environmental Impact Upstream (Material Production)	Difference Value @LC
	Difference Value for 10 years		
Carbon Dioxide (CO_2) [tonnes]	-1021.80	0.00	-1021.80
Sulphur Oxide (SO_x) [tonnes]	-6.90	0.00	-6.90
Nitrous Oxide (NO_x) [tonnes]	-1.40	N/A	-1.40
Solid Waste Burden [tonnes]	N/A	0.00	0.00
Net Present Value (NPV) [US$]	0.00	N/A	0.00

As shown in Figure 4.5, there are few differences between scenarios. Scenarios 1 and 3 have the same amount of CO_2, SO_x and NO_x emissions, while scenarios 2 and 4 release higher and lower amount of emissions respectively during the manufacturing process. The reason for that is explained above.

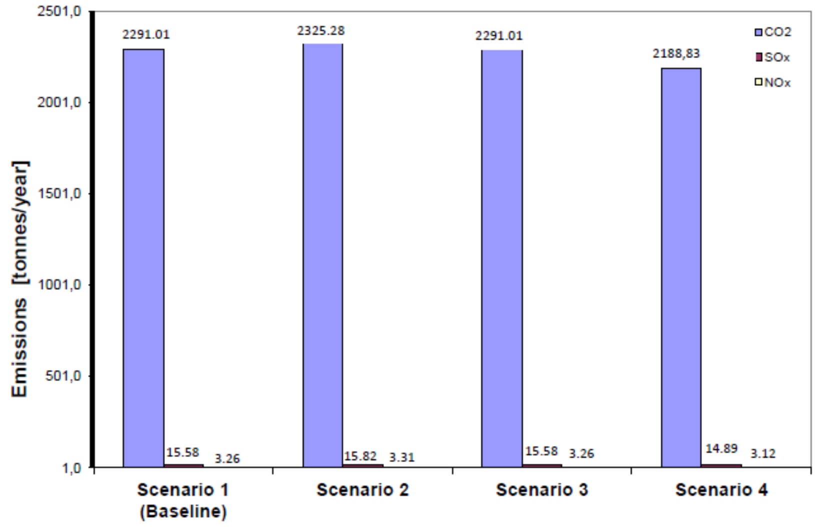

Figure 4.5 Amount of emissions produced in each scenario.

Regarding the NPV (see Figure 4.6), the Scenario 1 i.e. baseline, and Scenario 4 both have a NPV of US$0; scenario 2 has a substantial NPV of US$1,048,921; scenario 3 has a considerable value of US$5,375,131.

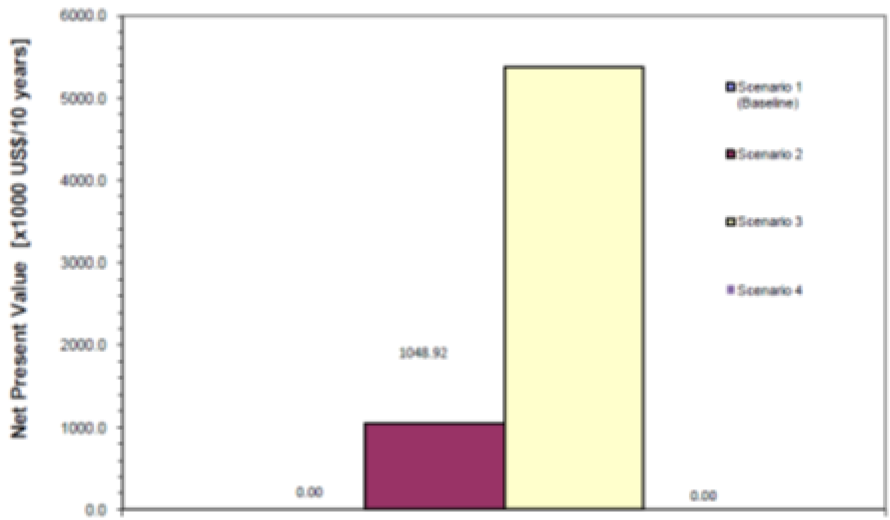

Figure 4.6 NPV in each scenario.

4.3 Summary

The selection of each case study is based on the research questions of this thesis. These scenarios are:

- scenario 1 (baseline): traditional manufacturing process, conventional equipment and 100% of electricity provided by the grid,
- scenario 2 (implementation of new technology): traditional manufacturing process, new equipment (reduction in material usage) and 100% of electricity provided by the grid),
- scenario 3 (reusing the material waste): partly-closed and/or closed manufacturing process, conventional equipment and 100% of electricity provided by the grid, and
- scenario 4 (electricity provided by the grid and the renewable): closed manufacturing process, conventional equipment and electricity and 95.54 % of electricity provided by the grid and 4.46 % by renewable.

The company used to carry out this study was a manufacturer of aluminium cans.

Scenario 3 “reuse of material waste” is very promising since the main emissions and raw material coming from the mines were reduced. As a result, the profit of the company for a period of 10 years has increased.

CHAPTER 5

CONCLUSIONS

5.1 Conclusions

People (customers) are becoming more and more aware of environmental issues. This situation in the future will lead companies to implement sustainable manufacturing taking into account the whole product life cycle i.e. from cradle to grave.

It has been discussed that sustainable manufacturing is related to the process to create products to satisfy the population's needs whilst keeping the negative impact on the environment as minimal as possible for future generations. Some sustainable manufacturing concepts for aluminium products available in the public domain have been analysed. In addition, different sustainability's metrics have been defined to quantify the environmental and economic performance such as: CO_2, SO_x and NO_x emissions, and NPV respectively.

Using the computational tool provided by NACFAM to assess the manufacturing process of aluminium cans in terms of the environmental impact and the economic implications for the company, it was possible to set three alternative approaches to do the same work described in the base line scenario, where the impact of implementing a new technology, the reuse of waste material and the use of renewable energy during the process were evaluated.

For example, assessing the baseline where 80,000 pounds of aluminium were used, the following was obtained: 2,291.01 tonnes of CO_2, 15.58 tonnes of SO_x and 3.26 tonnes of NO_x per annum. In the case of implementing a new technology (scenario

2), a higher environmental impact appears in terms of manufacturing process in comparison to the baseline scenario. The reason for this is that the new equipment is assumed to consume more energy (15,000 KWh rather than 10,000 KWh for the baseline scenario). But, the new equipment is more efficient through raw material usage which means lower cost of production leading to a more attractive NPV.

Now, if the waste material is reused (scenario 3), there is no difference between the baseline scenario and scenario 3, due to the equipment using the same amount of energy. Nonetheless, reusing the material waste leading to a reduction in the usage of raw material, it is possible to get a profit of US$5,375,131 for a period of ten years.

Finally, in the scenario 4 where electricity provided by the grid and renewable was used (having only 4.46% energy from renewable sources) it was possible to reduce the emissions. The reason for this is that less energy has been used from the grid which uses fossil fuels to produce electrical energy. In economic terms, it remains the same as the baseline due to of some renewable might be expensive.

Having to choose a scenario to implement, it would be scenario 3 as it was possible to decrease the amount of emission and raw material coming from the mines, whilst at the same time the profit of the company for a period of 10 years has risen.

We can observe that there are many ways to obtain the desired results keeping in balance both environmental and economic performance.

5.2 Recommendations for Future Work

The present work was performed at a concept level. Future students can take this research and assess any manufacturing process at a more detailed level using sophisticated software packages such as: Flexsim, Promodel, among others. Also, this work can be extended by means of implementation of the Life Cycle Assessment and Multidisciplinary Design Optimisation (MDO) to assess and optimise both environmental and economic impacts in the whole supply chain of an aluminium product.

OTHER PRELIMINARY LISTINGS

ABBREVIATIONS AND ACRONYMS

Al_2O_3	Alumina
BPMN	Business Process Modelling Notation
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CERES	Coalition For Environmentally Responsible Economics
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide-equivalents
CSM	Competitive Sustainable Manufacturing
D.C.	District of Columbia
DCFs	Discounted Cash Flows
DEA	Data Envelopment Analysis
DOE	Design of Experiments
DPSIR	Driving Force Pressure State Impact Response
EDM	Electrical Discharge Machining
EEA	European Environmental Agency
EIO-LCA	Economic Input-Output Life Cycle Assessment
eGRID	Emissions & Generation Resource Integrated Database
EMMA	Empresa Metal Mecánica de Aluminio
EPA	Environmental Protection Agency
E&RTD&I	Education and Research Technological Development and Innovation
ESET	Economy, Society, Environmental and Technology
ETs	Enabling Technologies
EU	European Union

GDP	Gross Domestic Product
GHG	Greenhouse Gases
GNP	Gross National Product
GRI	Global Reporting Initiative
GWP	Global Warming Potential
IDs	Industrial Districts
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
ISO	International Organisation for Standardisation
JIT	Just In Time
Kg	Kilogram
KWh	Kilowatt hour
lbs	Pound (mass)
LCA	Life Cycle Assessment
LCSP	Lowell Centre For Sustainable Production
MDO	Multidisciplinary Design Optimisation
mm	Millimetre
MNA	Manufacturing Needs Analysis
MW	Mega Watt
NACFAM	National Council for Advanced Manufacturing
NI	National Income
N_2O	Nitrous Oxide
NO_x	Nitrogen Oxide
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
OPUS	Optimizing Production Using Simulation
p.a.	Per Annum
PNA	Analysis Of The Needs For Productivity

PSR	Pressure State Response
RMfPA	Reference Model for Proactive Action
S.A.	Sociedad Anónima
SD	Sustainable Development
SDIs	Sustainable Development Indicators
SEIs	Socio Ecological Values
SI	Strategic Intelligence
SIA	Subaru of Indiana
SM	Sustainable Manufacturing
SO_2e	Sulphur Dioxide Equivalents
SO_2	Sulphur Dioxide
SO_x	Sulphur Oxide
UK	United Kingdom
UN	United Nations
UNCSD	United Nation Commission for Sustainable Development
UNEP	United Nations Environment Program
US	United States
U.S.A.	United States of America
USDOE	United States Department of Energy
US$	American Dollar
v/v	Validation and Verification
WBCSD	World Business Council For Sustainable Development
WIP	Work In Process
°C	Degree Celsius
3R	Reuse-Remanufacture-Recycle
6R	Reduce-Recover-Redesign-Reuse-Recycle-Remanufacture

LIST OF REFERENCES

Accounting Tools (2014). Accounting Dictionary. http://www.accountingtools.com/definition-net-present-value (accessed on 22nd February 2014).

Ad. J. Ron. (1998). Sustainable Production: The Ultimate Result of a Continuous Improvement. In: *International Journal of Production Economics*, 56-57, (1), 99-110.

Aktiva Servicios Financieros (2013). Estudios Sectoriales. http://aktiva.com.co/blog/Estudios%20sectoriales/2013/acero_metalmecanico.pdf (accessed on 17th January 2014).

Albino, V. and Kühtz, S. (2003). Assessment of Environmental Impact of Production Processes in Industrial Districts Using Input-output Modeling Techniques. In: *Journal of Environmental Informatics*, 1 (1), 7-20.

Anon. (1991). WITNESS User Manual, AT&T Istel Visual Interactive Systems, Ltd., Redditch, UK.

Anon. (1991). ProModel PC User's Guide, Production Corporation, Warwick, UK.

Anon. (1992). SIMFACTORY II.5 Reference Manual and User's Guide, CACI Products Company, La Jolla, USA.

Anon. (2014). Renewable Energy and Other Alternative Energy Sources) (www.dmme.virginia.gov/DE/LinkDocuments/HandbookAlternativeEnergy.pdf) (accessed on 30th March 2014).

Baca Currea, G. (2002). Ingeniería Económica. Fondo Educativo Panamericano, Bogotá, Colombia.

Battista, C. Dello Stritto, G., Giordano, F., Iannone, R and Schiraldi, M. (2011). Manufacturing Systems Modelling and Simulation Software Design: a Reference Model. In: *Annals of DAAAM for 2011 & Proceedings of the 22nd International DAAAM Symposium "Intelligent Manufacturing & Automation: Power of Knowledge and Creativity"*, 23-26th November 2011, Vienna, Austria.

Beamon, B. M. (2008). Sustainability and the Future of Supply Chain Management. In: *Journal of Operations and Supply Chain Management*, 1 (1), 4-18.

Berke, P. and Manta, M. (1999). Planning for Sustainable Development: Measuring Progress in Plans, Working Paper, Lincoln Institute of Land Policy. https://www.lincolninst.edu/pubs/dl/58_BerkeManta99.pdf (accessed on 15th May 2013).

Bovone, M., De Ferrari, V. and Manuelli, R. (1989). How to Choose an Useful Simulation Software. In: *Proceedings of the 1989 European Simulation Multiconference*, SCS, San Diego, USA.

Brundtland, G. H. (1987). Report of the World Commission on Environment and Development: Our Common Future. United Nations. http://conspect.nl/pdf/Our_Common_Future-Brundtland_Report_1987.pdf (accessed on 20th May 2013).

Chung, Y.G., White, D.A. (1989). Simulation with PC Model. In: *Proceedings of the 1989 Winter Simulation Conference Software Systems*, San Jose, CA.

Clementson, A.T. (1991). The ECSL Plus System Manual. Available from Clementson A.T., The Chestnuts, Princess Road, Windermere, Cumbria, UK.

Conway, R., Maxwell, W.L., McClain, J. and Worona, S.L. (1988). User's Guide to XCELL+. The Scientific Press, Redwood CA.

Culaba, A.B. and Purvis, M.R.I. (1999). A Methodology for the Life Cycle and Sustainability Analysis of Manufacturing Processes. In: *Journal of Cleaner Production*, 7 (6), 435-445.

Douglas, J.M. (1992). Process Synthesis for Waste Minimization. In: *Industrial & Engineering Chemistry Research*, 31 (1), 238-243.

Bringezu, S., Schütz, H. and Bosch, P. (2001). Total Material Requirement of European Union, Technical Report No. 56, European Environment Agency, Copenhagen, Denmark.

Egilmez, G., Kucukvar, M. and Tatari, O. (2013). Sustainability Assessment of U.S. Manufacturing Sectors: an Economic Input Output-Based Frontier Approach. In: *Journal of Cleaner Production*, 53, 91-102.

eGRID (2007). U.S. EPA's Emissions & Generation Resource Integrated Database (eGRID). Version 1 contains the complete release of year 2005 data. The data are organised to reflect the owner, operator and electric grid configuration as of October 1, 2007.
www.epa.gov/cleanenergy/egrid (accessed on 25th June 2013).

El-Halwagi, M.M. and V. Manousiouthakis (1989). Synthesis of Mass Exchange Networks. In: *AlChE Journal*, 35 (8), 1233-1250.

Ekvall, T. and Finnveden, G. (200)1. Allocation in ISO 14041 – A Critical Review. In: *Journal of Cleaner Production*, 9 (3), 197-208.

ENERGY STAR Portfolio Manager (2011). Methodology for Greenhouse Gas Inventory and Tracking Calculations, November 2011.

Engineering Council UK (2009). Guidance on Sustainability for the EngineeringProfession. United Kingdom. http://www.engc.org.uk/ecukdocuments/internet/document%20library/Guidance%20on%20Sustainability.pdf (accessed on 27th July 2013).

European Aluminium Association (2013). Environmental Profile Report for the European Aluminium Industry. Data for the year 2010. http://www.alueurope.eu/wp-content/uploads/2011/10/Environmental-Profile-Report-for-the-European-Aluminium-Industry-April-2013.pdf (accessed on 11th August 2013).

Fava, J., Denison, R., Jones, B., Curran, M.A., Vigon, B., Selke, S., and Barnum, J. (1991): A Technical Framework for Life-Cycle Assessments. Workshop Report. Society of Environmental Toxicology and Chemistry, Washington D.C.

Finnveden, G. (1999). Methodological Aspects of Life Cycle Assessment of Integrated Solid Waste Management Systems. In: *Resources, Conservation and Recycling* 26, 173-187.

Flower, J.R., Bikos, S.C. and Johnson, S.W. (1993). The graphical mass balance in the early design of clean processes. In: *Transactions of IChemE*, Part B, g, 194-201.

Global Reporting Initiative (2002a). The Global Reporting Initiative - An Overview. Global Reporting Initiative, Boston, USA. https://www.globalreporting.org/reporting/reporting-framework-overview/Pages/default.aspx (accessed on 28th January 2014).

Global Reporting Initiative (2002b). Sustainability Reporting Guidelines 2002 on Economic and Social Performance. Global Reporting Initiative, Boston, USA. https://www.globalreporting.org/reporting/reporting-framework-overview/Pages/default.aspx (accessed on 28th January 2014).

Godfrey, L. and Todd, C. (2001). Defining Thresholds for Freshwater Sustainability Indicators within the Context of South African Water Resource Management. 2nd WARFSA/Waternet Symposium: Integrated Water Resource Management: Theory, Practice, Cases. Cape Town, South Africa.

Haller, A.-P. (2012). Concepts of Economic Growth and Development. Challenges of Crisis and of Knowledge. In: *Economy Transdisciplinarity Cognition Journal*, 15 (1), 66–71.

Harrell, C.R. and Tumay, K. (1995). Simulation Made Easy: A Manager's Guide. Industrial Engineering and Management Press.

Heilala, J., Vatanen, S., Tonteri, H., Montonen, J., Lind, S., Johansson, B. and Stahre, J. (2008). Simulation-Based Sustainable Manufacturing System Design. In: *Proceedings of the 2008 Winter Simulation Conference*, Miami, USA.

Herron, C. and Braiden, P. M. (2006). A Methodology for Developing Sustainable Quantifiable Productivity Improvement in Manufacturing Companies. In: *International Journal of Production Economics*, 104 (1), 143–153.

Holmberg, J., Karlsson, S., 1992. On Designing Socio-ecological Indicators. In: *Society and the Environment: A Swedish Research Perspective Ecology, Economy & Environment.* 2, 89-106.

Hutchins, M.J., Robinson, S.L, Dornfeld, D.. (2013). Understanding life cycle social impacts in manufacturing: A processed-based approach. In: *Journal of Manufacturing Systems* 32, (4), 536-542.

Ijomah, W.L., McMahon, C.A., Hammond, G.P. Newman, S.T. (2007). Development of design for remanufacturing guidelines to support sustainable manufacturing. In: *Robotics and Computer-Integrated Manufacturing*. 23, (6), 712-719.

Inman, W. (2006). A Clean, Green Set of Wheels. Industrial Engineer, 38 (4).

Intergovernmental Panel on Climate Change (1995). The Science of Climate Change, Cambridge, UK, Cambridge University Press, http://www.ipcc.ch/ipccreports/assessments-reports.htm (accessed on 13th July 2013).

Intergovernmental Panel on Climate Change (2007). Fourth Assessment Report (AR4): Climate Change 2007: Synthesis Report. http://www.ipcc.ch/publications_and_data/ar4/syr/en/mains1.html (accessed on 13th July 2013).

Inventory of U.S. Greenhouse Gas and Sinks (1990-2005). "USEPA #430-R-07-002, April 2009. Table 2-16: U.S. Greenhouse Gas Emissions by Economic Sector and Gas with Electricity-Related Emissions.

Inventory of U.S. Greenhouse Gas Emissions and Sinks (1990-2005). Tables 3-3, 3-14, & 3-15.

ISO (1997). Environmental Management - Life Cycle Assessment - Principles and Framework. http://web.stanford.edu/class/cee214/Readings/ISOLCA.pdf (accessed on 20th August 2013).

Jayal, A.D., Badurdeen, F., Dillon Jr., O.W. and Jawahir, I.S. (2010). Sustainable Manufacturing: Modeling and Optimization Challenges at the Product, Process and Systems Levels. In: *CIRP Journal of Manufacturing Science and Technology*, 2 (3), 144–152.

Kaebernick, H., Kara, S., Sun, M. (2003). Sustainable Product Development and Manufacturing by Considering Environmental Requirements. In: *Robotics and Computer-Integrated Manufacturing*. 19, (6), 461-468.

Kates, R.W., Clark, W.C., Corell, R., Hall, M.J., Jaeger, C.C., Lowe, I., McCarthy, J.J., Schellnhuber, H.J., Bolin, B., Dickson, N.M., Faucheux, S. Gallopin, G.C., Grubler, A., Huntley, B., Jager, J., Jodha, N.S., Kasperson, R.E., Mabogunje, A., Matson, P., Mooney, H., Moore, B., O`Roirdan, T., and Svedin, U. (2001). Environment and Development, Sustainability Science. In: *Science.* 292 (5517), 641-642.

Lancker, E. and Nijkamp, P., (2000). A Policy Scenario Analysis of Sustainable Agricultural Development Options: a Case Study for Nepal. In: *Impact Assessment and Project Appraisal*, 18 (2), 111-124.

Law, A.M. and Kelton, W.D. (1991). Simulation Modelling and Analysis. 2nd edition, McGraw-Hill, Singapore.

PE Americas (2010). Life Cycle Impact Assessment of Aluminium Beverage Cans. *Prepared for: Aluminum Association*, Inc. Washington, USA.

Lundin, M., (2003). Indicators for Measuring the Sustainability of Urban Water Systems - A Life Cycle Approach. http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=AB0044C80D45801D87920A84BAF2E2A3?doi=10.1.1.195.818&rep=rep1&type=pdf (accessed on 15th April 2014).

Meadows, D., (1998). Indicators and Information Systems for Sustainable Development - A Report to the Balaton Group. The Sustainability Institute. Hartland, USA. http://www.comitatoscientifico.org/temi%20SD/documents/@@Meadows%20SD%20indicators.pdf (accessed on 15th April 2014).

Minitab 16 User’s Manual, 2010.

Montgomery, D.C. (2012). Design and Analysis of Experiments, 8 Edition, Wiley.

NACFAM (2010a). White Paper: Development, Release and Open-Sourcing of Sustainability Framework Model, June, 2010, Washington, USA.

NACFAM (2010b). Examples with Explanations for Using NACFAM’s Sustainability Framework Model, June, 2010, Washington, USA.

Nagalingam, S.V., Kuik, S.S. and Amer, Y. (2013) Performance Measurement of Product Returns with Recovery for Sustainable Manufacturing. In: *Robotics and Computer-Integrated Manufacturing*, 29, (6), 473–483.

Ness, B., Urbel-Piirsalu, E., Anderberg, S. and Olsson, L., (2007). Categorising Tools for Sustainability Assessment. In: *Ecological Economics*, 60 (3), 498-508.

Norgate, T.E., Jahanshahi, S. and Rankin, W.J. (2007). Assessing the Environmental Impact of Metal Production Processes. In: *Journal of Cleaner Production*, 15 (8-9), 838-848.

OECD, 1998. Towards Sustainable Deveopment: Environmental Indicators, Paris, OECD.

Organisation for Economic Co-operation and Development (OECD) (2002b). OECD Guidelines for Multinational Enterprises. Annual Report 2002.

Organisation for Economic Co-operation and Development (OECD) (2014). First Environmental Performance Review of Colombia.
http://www.oecd.org/environment/colombia-must-do-more-on-environment-for-sustainable-economic-growth-says-oecd.htm (accessed on 10th May 2014).

Organisation for Economic Co-operation and Development (OECD) (2002a). An update of the OECD Composite leading Indicators. Short-term economic Statistics division, Statistics Directorate/OECD. http://www.oecd.org (accessed on 10/04/2014).

Pedgen, C.D., Sadowski, R.P. and Shannon, R.E. (1991). Introduction to Simulation Using SIMAN: Instructor`s Manual. McGraw Hill Higher Education.

Pezzey, J. (1992). Sustainable Development Concepts: an Economic Analysis, World Bank Environment Paper Number 2, The World Bank, Washington, USA.

Pidd, M. (1989). Choosing discrete simulation software. Useful Features to Look for and what to Ask the Salesman. In: *OR Insight*, 2 (3).

Prescott-Allen, R., 1995. Barometer of Sustainability: a Method of Assessing Progress towards Sustainable Societies. PADATA, Victoria, Canada.

Pritsker, A.A.B., Rolston L.J., Floss P., (1986). Introduction to Simulation and SLAM II (Soluition Manual).

Ramachandran, N., 2000. Monitoring Sustainability: Indices and Techniques of Analysis. Concept Publishing Company, New Delhi.

Redclift, M. (1989). Sustainable Development: Exploring the Contradictions. Routledge, London, UK.

Riebeek, H. (2007). Global Warming.
http://earthobservatory.nasa.gov/Features/GlobalWarming/global_warming_2007.pdf (accessed on 18th September 2013).

Russell, E.C. (1999). Building Simulation Models with SIMSCRIPT II.5, CACI Products Company, La Jolla, CA.

Schriber, T.J. (1991). An Introduction to Simulation Using GPSS/ H, John Wiley, New York, NY.

Simpson, T. W., Peplinski, J.D., Koch, P. N. and Allen, J. K. (1997). On the Use of Statistics in Design and the Implications for Deterministic Computer Experiments. In: *Design Theory and Methodology – DTM'97,* Sacramento, CA.

Singh, R. K., Murty, H.R.,Gupta, S.K. and Dikshit, A.K. (2012). An Overview of Sustainability Assessment Methodologies. In: *Ecological Indicators*, 15 (1), 281–299.

Smeets, E., Weterings, R., (1999). Environmental Indicators: Typology and Overview. Technical Report No 25 European Environment Agency (EEA), Copenhagen, Denmark.

Stefanis, S. K., Livingston, A.G. and Pistikopoulos, E. N. (1995). Minimizing the Environmental Impact of Process Plants: A Process Systems Methodology. *In: Computers & Chemical Engineering*, 19 (1), 39-44.

Sustainable Manufacturing Portal (2010). Life Cycle Strategies Manual. . http://www.centreforsmart.co.uk/smp/lcsm_materialextraction.php (accessed on 10th November 2010).

Sustainability Standards Portal (2010). Overview of sustainable manufacturing. http://www.mel.nist.gov/msid/SSP/introduction/manufacturing.html (accessed on 10th Novevember 2010).

Taguchi, G. and Konishi, S. (1987). Orthogonal Arrays and Linear Graphs. American Supplier Institute, Dearborn, USA.

The U.S. Department of Commerce's. Sustainable Manufacturing Initiative (SMI) International Trade Administration: A True Public-Private Dialogue. Matthew C. Howard Program Leader. http://www.oecd.org/sti/ind/45010349.pdf (accessed on 8th November 2013).

Thompson, M.B. (1989). AutoMod II: the System Builder. In: *Proceedings of the 21st Conference on Winter Simulation,* ACM New York, NY, USA.

United Nations, Department of Economic and Social Affairs (Population Division) (2007). World Population Prospects: the 2006 Revision. United Nations Population N.Y.

United States Energy Information Administration (2007). Annual Energy Outlook 2008 (early release), December.

U.S. Energy Information Administration (2007). Annual Energy Review http://www.eia.gov/totalenergy/data/annual/archive/038407.pdf (accessed on 30th May 2013).

U.S Department of Energy (DOE), National Renewable Energy Laboratory (NREL). (2001). Renewable Energy: An Overview (http://www.nrel.gov/docs/fy01osti/27955.pdf) (accessed on 28th March 2014).

Wackernagel, M., Rees, W., (1998). Our Ecological Footprint: Reducing Human Impact on the Earth. New Society Publishers.

Wang, Y.P. and R. Smith (1994). Wastewater minimization. In: *Chemical Engineering Science*, 49 (7), 981-1006.

Warhurst, A., (2002). Sustainability Indicators and Sustainability Performance Management. Report to the Project: Mining, Minerals and Sustainable Development (MMSD). International Institute for Environment and Development (IIED). Warwick, England.
http://www.iied.org/mmsd/mmsd_pdfs/sustainability_indicators.pdf (accessed on 10th March 2014).

World Business Council for Sustainable Development (WBCSD). (1999). Eco-efficiency Indicators and Reporting: Report on the Status of the Project's Work in Progress and Guidelines for Pilot Application. Geneva, Switzerland.

Vlatka, H. and Ray J, P. (1999). A Guidelines for Selection of Manufacturing Simulation Software. In: *IIE Transactions*, 31 (1), 21-29.

Ziout , A., Azab, A., Altarazi, S., ElMaraghy. W.H. (2013). Multi-criteria Decision Support for Sustainability Assessment of Manufacturing System Reuse. In: *CIRP Journal of Manufacturing Science and Technology*, 6 (1), 59-69.

BIBLIOGRAPHY

Ball, P. D., Evans S., Levers, A., Ellison, D. (2009). Zero Carbon Manufacturing Facility — towards Integrating Material, Energy and Waste Process Flows. In: *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 223 (9), 1085-1096.

Ciegisl, R., Ramanauskiene, J. and Martinkus, B. (2009). The Concept of Sustainable Development and its Use for Sustainability Scenarios. In: *Inzinerine Ekonomika-Engineering Economics*, 2, 28-37.

Colmenares Quintero, R. F. (2009). Techno-economic and Environmental Risk Assessment of Innovative Propulsion Systems for Short-range Civil Aircraft, PhD Thesis, Cranfield University, UK.

Despeisse, M. (2013). Sustainable Manufacturing Tactics and Improvement Methodology: a Structured and Systematic Approach to Identify Improvement Opportunities, PhD Thesis, Cranfield University, UK.

Despeisse, M., Oates, M. R. and Ball P. (2013). Sustainable Manufacturing Tactics and Cross-functional Factory Modelling. In: *Journal of Cleaner Production*, 42, 31–41.

Esty, D. C. and Winston, A. S. (2009). Green to Gold: How Smart Companies Use Environmental Strategy to Innovate, Create Value, and Build Competitive Advantage. John Wiley & Sons, Inc., Hoboken, USA.

Faber, N., Jorna, R. and Van Engelen, J. (2005). The Sustainability of "Sustainability" —a Study into the Conceptual Foundations of the Notion of "Sustainability". In: *Journal of Environmental Assessment Policy and Management*, 7 (1), 1–33.

Glavic, P. and Lukman, R. (2007). Review of Sustainability Terms and their Definitions. In: *Journal of Cleaner Production*, 15, 1875-1885.

Jawahir, I.S. (2007). Sustainable Manufacturing: the Driving Force for Innovative Products, Processes and Systems for Next Generation Manufacturing. http://www.ncsl.org/Portals/1/Documents/employ/Jawahir-Manuf.pdf (accessed on 20th June 2013).

Jorna, R. J. (2004). The Concept of "Sustainability"and Sustainable Innovation: an Attempt to Reconceptualise, Lecture Presented at Netherlands Institute for Advanced Science (NIAS).

http://www.sustainableorganizations.org/Concept_of_Sustainability.pdf (accessed on 15th July 2013).

Mahayuddin, Z. R. and Tjahjono, B. (2010). Simulation Modelling by Classification of Problems: a Case of Assembly Lines. In: *Proceedings of the Operational Research Society Simulation Workshop 2010 (SW10),* Worcestershire, England, 23-24 March 2010.

Masanet, E. and Chang, Y. (2014). How Green is that Product? An Introduction to Life Cycle Environmental Assessment, Coursera Lecture Notes, Northwestern University, Evanston, USA.

Nakano, M. (2010). A Conceptual Framework for Sustainable Manufacturing by Focusing on Risks in Supply Chains. In: *Proceedings of Advances in Production Management Systems. New Challenges, New Approaches*, IFIP Advances in Information and Communication Technology, 338, 160-167.

Nambiar, A. N. (2010). Challenges in Sustainable Manufacturing. In: *International Conference on Industrial Engineering and Operations Management*, Dhaka, Bangladesh, January 9-10 2010.

Pham, D. T. and Castellani, M. (2009). The Bees Algorithm: Modelling Foraging Behaviour to Solve Continuous Optimization Problems. In: *Journal of Mechanical Engineering Science*, 223 (12), 2919-2938.

Pham, D.T., Darwish, A. H. and Eldukhri, E.E. (2009). Optimisation of a Fuzzy Logic Controller using the Bees Algorithm. In: *International Journal of Computer Aided Engineering and Technology*, 1 (2), 250-264.

Saez, M. J. and Riquarts, K. (1995). El Desarrollo Sostenible y el Futuro de la Enseñanza de las Ciencias, Investigación y Experiencias Didácticas. http://ddd.uab.cat/pub/edlc/02124521v14n2p175.pdf (accessed on 22nd August 2013).

Seliger, G., Kim, H-J., Kernbaum, S. and Zettl, M. (2008**).** Approaches to Sustainable Manufacturing. In: *International Journal of Sustainable Manufacturing*, 1 (1/2), 58 – 77.

Smith, L. and Ball, P. (2012). Steps towards Sustainable Manufacturing through Modelling Material, Energy and Waste Flows. In: *International Journal of Production Economics*, 140 (1), 227-238.

Tobey, J. A. (1989). Economic Development and Environmental Management in the Third World Trading-off Industrial Pollution with the Pollution of Poverty. In: *Habitat International*, 13 (4), 125-135.

Turner, G. (2008). A Comparison of the Limits to Growth with Thirty Years of Reality. Socio-Economics and the Environment. In: Discussion *CSIRO Working Paper Series 2008-09*, Canberra, Australia.

Westkämper, E. (2008). Manufuture and Sustainable Manufacturing. In: *The 41st CIRP Conference on Manufacturing Systems*, Tokyo, Japan, May 26–28 2008.

APPENDICES

APPENDIX A: Data used for simulations

Table A.1 Inputs values.

INPUTS	-10%	BASE LINE	10%
Average annual electricity use (Kwh)	558493.50	620548.33	682603.17
Electricity price ($/Kwh)	0.06	0.07	0.07
Average annual gas use (mmBTU)	5720.70	6356.33	6991.96
Natural gas price ($/thousand cubic feet)	4.94	5.49	6.04
Average annual water use (HCF)	898.40	998.23	1098.05
Price of water ($/HCF)	2.11	2.35	2.58
Material usage (lbs)	3373072.61	3747858.46	4122644.30
Price of material ($/lb)	0.89	0.99	1.08
Chemical usage (lb)	2984.18	3315.75	3647.33
Price of chemicals ($/ton)	22.50	25.00	27.50
Solid waste (ton)	572.78	636.42	700.06
Hazardous waste (ton)	0.18	0.20	0.22
Non-hazardous waste (ton)	9.93	11.03	12.14

Table A.2 Array showing all inputs and its values.

	Avg annual electricity use (Kwh)	Electricity price ($/Kwh)	Avg annual gas use (mmBTU)	Natural gas price ($/thousand cubic feet)	Avg annual water use (HCF)	Price of water ($/HCF)	Material usage (lbs)	Price of material ($/lb)	Chemical usage (lb)	Price of chemicals ($/ton)	Solid waste (ton)	Hazardous waste (ton)	Non-hazardous waste (ton)
1	558493.50	0.06	5720.70	4.94	898.40	2.11	3373072.61	0.89	2984.18	22.50	572.78	0.18	9.93
2	558493.50	0.06	5720.70	4.94	898.40	2.11	3373072.61	1.08	3647.33	27.50	700.06	0.22	12.14
3	558493.50	0.06	5720.70	6.04	1098.05	2.58	4122644.30	0.89	2984.18	22.50	572.78	0.22	12.14
4	558493.50	0.06	5720.70	6.04	1098.05	2.58	4122644.30	1.08	3647.33	27.50	700.06	0.18	9.93
5	558493.50	0.07	6991.96	4.94	898.40	2.58	4122644.30	0.89	2984.18	27.50	700.06	0.18	9.93
6	558493.50	0.07	6991.96	4.94	898.40	2.58	4122644.30	1.08	3647.33	22.50	572.78	0.22	12.14
7	558493.50	0.07	6991.96	4.94	898.40	2.58	4122644.30	1.08	3647.33	22.50	572.78	0.22	12.14
8	558493.50	0.07	6991.96	6.04	1098.05	2.11	3373072.61	1.08	3647.33	22.50	572.78	0.18	9.93
9	682603.17	0.06	6991.96	4.94	1098.05	2.11	4122644.30	0.89	3647.33	22.50	700.06	0.18	12.14
10	682603.17	0.06	6991.96	4.94	1098.05	2.11	4122644.30	1.08	2984.18	27.50	572.78	0.22	9.93
11	682603.17	0.06	6991.96	6.04	898.40	2.58	3373072.61	0.89	3647.33	22.50	700.06	0.22	9.93
12	682603.17	0.06	6991.96	6.04	898.40	2.58	3373072.61	1.08	2984.18	27.50	572.78	0.18	12.14
13	682603.17	0.07	5720.70	4.94	1098.05	2.58	3373072.61	0.89	3647.33	27.50	572.78	0.18	12.14
14	682603.17	0.07	5720.70	4.94	1098.05	2.58	3373072.61	1.08	2984.18	22.50	700.06	0.22	9.93
15	682603.17	0.07	5720.70	6.04	898.40	2.11	4122644.30	0.89	3647.33	27.50	572.78	0.22	9.93
16	682603.17	0.07	5720.70	6.04	898.40	2.11	4122644.30	1.08	2984.18	22.50	700.06	0.18	12.14

APPENDIX B: A generic process describing how the proposed method can be applied to any manufacturing industry.

Firstly, it is necessary to start with the **General Input and Assumptions tab**.

- ❖ Federal Tax Rate needs to be inserted in cell C6, in case this value is not available 35% needs to be assumed.
- ❖ Purchase year of the equipment needs to be introduced into cell C9.
- ❖ eGRID emission factor or State –Specific emission factor must be chosen from drop-off menu given in cell C13.
- ❖ Electricity grid provider can be selected from cell C14.
- ❖ A cost of funds number must be given in cell C34. In case there is no information available regarding how the company estimates this, a 3% can be assumed.
- ❖ Discount rate applicable to company projects needs to be included in cell C46.
- ❖ Discount rate given in cell C46 needs to be introduced in cell C47 (warning: for the simulations to work, a non-zero value needs to be in cell C47).

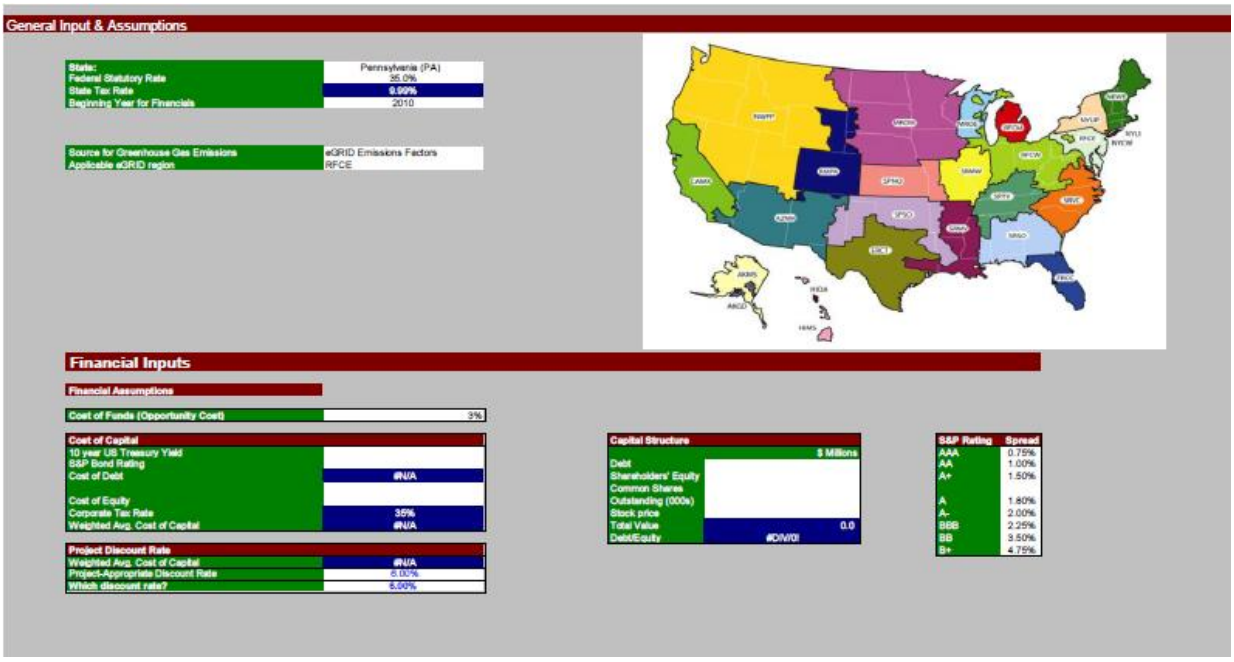

Figure B.1 General Input and Assumptions tab. Source: NAFCAM (2010a).

<u>**Manufacturing Process Input tab**</u>

- ❖ Annual Energy Use for the facility needs to be inserted in cell C14.
- ❖ A percentage of annual electricity usage that the company gets from the grid must be introduced in cell C15; if it is less than 100%, then the percentage corresponding to renewables needs to be given in cell C17 and the one for on-site non-renewable in cell C19.
- ❖ Electricity price is provided in cell C16.
- ❖ If the percentage of the electricity is less than 100%, then the price of the renewable energy must be entered in cell C18 and the on-site non-renewable energy price in cell C20.
- ❖ Annual growth factor for electricity price must be introduced in cell D16. A good estimate can be 3%.

- From drop-down menu given in cell C21, the combustor type for natural gas can be selected. The combustor type can be obtained from the natural gas provider.
- If the natural gas combustor is controlled or uncontrolled can be defined in cell C22.
- The average annual amount of natural gas used by the facility, process, or manufacturing of the product under study is provided in cell C23.
- The natural gas price is typed in cell C27.
- Annual growth factor for natural gas price must be introduced in cell D27. A good estimate can be 3%.
- Average annual water usage in hundred cubic feet (HCF) is entered in cell C28.
- The price of water is given in cell C29.
- Annual growth factor for water price must be introduced in cell D29.
- In order to avoid errors during the calculations, number 1 is given to cells C61, C71, C88, C91, C94 and C103.
- From drop-down menu given in cell A41, a metal of interest must be picked.
- Used average amount of metal in lbs per annum needs to be entered in cell C41.
- The price of metal per lb. is entered in cell C42.
- Annual growth factor for electricity price must be introduced in cell D42. A good guess can be 2%.

Manufacturing Process Input		
	2010	2011
Total Number of Products Manufactured	-	
Expenses		
Baseline	Baseline	Growth Factors
Energy & Water		
Average Annual Electricity Use (kWh)	4,000,000	
Percentage from grid	100%	
Electricity price ($/kWh)	$ 0.0701	3%
Percentage from Renewable Energy		
Electricity price ($/kWh)		
Percentage from Onsite non-Renewable Energy		
Electricity price ($/kWh)		
Combustor Type	Large Wall-Fired Boilers Controlled - Flue gas recirculation	
Natural Gas Controlled or Uncontrolled Burner	N2O (pounds) Controlled low NOx burner	
Average Annual Natural Gas Use (mmBtu) if known in mmBtu		
Average Annual Natural Gas Use (million cubic feet)	-	
Average Annual Natural Gas Use (thousand cubic feet) only if known		
Average Annual Natural Gas Use (thousand cubic feet)	-	
Natural gas price ($/thousand cubic feet)	$ 15.21	
Average Annual Water Use (HCF)		
Price of Water ($/HCF)		
Material		
Annual Material Input (all in lbs.)		
Iron (lbs.)		
Price ($/lb.)		
Average Distance Transported		
Cost for alternative form of metal purchased ($/lb.)		
Titanium: Becher and Kroll processes		
Price ($/lb.)		
Average Distance Transported		
Cost for alternative form of metal purchased ($/lb.)		
Aluminium: Bayer refining, Halle-Heroult smelting conventional	80,000	
Price ($/lb.)	$ 20.00	2%
Average Distance Transported		
Cost for alternative form of metal purchased ($/lb.)		

Figure B.2 Manufacturing Process Input tab. Source: NAFCAM (2010a).

<u>Outputs - Results</u>

Finally, the results can be seen in **<u>Project Output Dashboard tab</u>**.

- ❖ Environmental performance indicators for a period of 10 years: upstream impacts (GHG emissions in cell D8, SO_x emissions in cell D9 and Solid Waste Burden in cell D10) and manufacturing impacts (GHG emissions in cell I5, SO_x emissions in cell I6 and NO_x emissions in cell I7).
- ❖ Economic performance indicators for a period of 10 years: Total Cumulative Net Present Value (NPV) in cell O7 and Internal Rate of Return (IRR) in cell O8 for the baseline scenario and NPV in cell O13 and IRR in cell O14 for comparison scenario.

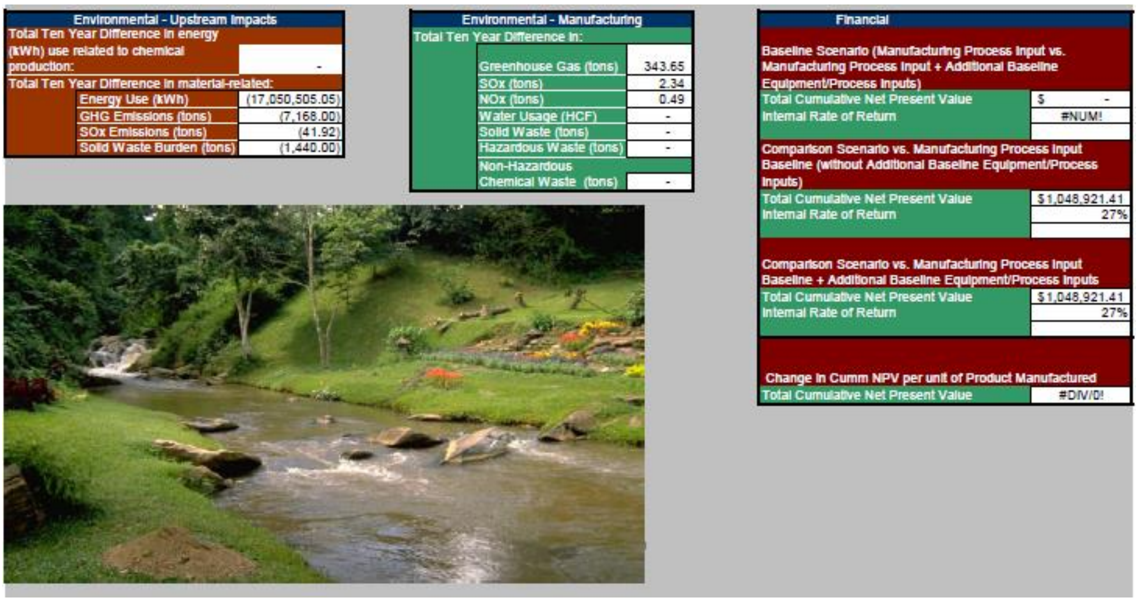

Figure B.3 Project Output Dashboard tab. Source: NAFCAM (2010a).