Mauritius Research Council

Use of Weathering Steel as a Sustainable Material in Mauritius

Final Report

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FINAL REPORT

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Use of Weathering Steel as a Sustainable Material in Mauritius

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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DECLARATION

I certify to the best of my knowledge (1) the statement herein (excluding scientific hypotheses and scientific opinion) are true and complete, and (2) the text and graphics in this report as well as any accompanying publications or other documents, unless otherwise indicated, are the original work of the signatories or of individuals working under their supervision. I understand that willfully making a false statement or concealing a material fact in this report or any other communication submitted to MRC is a criminal offense.

Principal Investigator Signature:		Date: 9 October 2017

ABSTRACT

Carbon steels, though being the most commonly used metal in Mauritius, are prone to atmospheric corrosion attack. One method to curb corrosion is to use corrosion resistant materials such as weathering steel. Weathering steel is, however, not commonly used locally.

The aim of the project was, therefore, to investigate the feasibility of using weathering steel instead of carbon steel in Mauritius. This was performed through a Life Cycle Assessment for carbon steel in Mauritius and determining the atmospheric corrosion behaviour of weathering steel in the local atmosphere.

The Life Cycle Assessment was performed using openLCA 1.6.3 software. A proper flow of the carbon steel was established where all stages of life of the metal were thoroughly established, including recycled scraps. The atmospheric corrosion behaviour of weathering steel was determined through outdoor exposures at two sites, namely, Port Louis and Reduit. Mild steel samples were also exposed for comparison purposes.

The outdoor exposure of the metal samples revealed that the corrosivity of the atmospheres fell in the category C4, according to ISO 9223. Weathering steel corroded lesser than the mild steel samples by more than 30%.

The LCA for carbon steel has shown that steel production has the greatest environmental impact in the boundary system. The use of weathering steel provides the alternative to substantially decrease the environmental impact through lesser imports. Financially, the price of weathering steel and mild steel is nearly equal. Hence, weathering steel should be proposed as an alternative to carbon steel in Mauritius.

1. INTRODUCTION

Imports for iron and steel have increased from 46,000 tonnes in 2000 to 68,200 tonnes in 2007 (Central Statistical Office, 2011) with now, reaching above 110,697 tons. Carbon steels, though being the most commonly used metal in Mauritius, are prone to atmospheric corrosion attack and their use, especially in the construction of buildings and other structures, obviously incurs substantial corrosion costs. Corrosion has also been very detrimental to the society leading to accidents and even losses of human lives. In Mauritius, in one such study, the cost of atmospheric corrosion was estimated to be USD39 million in 2012 (Surnam, 2012). This is a very large amount of money which gives an idea of the potential saving that can be envisaged by properly tackling the problem of atmospheric corrosion. Therefore an increase in importation of such material entails in its trail an increase in corrosion cost which is not line with the concept of sustainable island where material sustainability is a major component. With such large amount of low carbon steel used nowadays, the Mauritius Sustainable Island project can arguably be considered a farfetched idea. One method to curb corrosion is the use of the corrosion resistant material such as weathering steel.

Weathering steel has been successfully used in many countries worldwide in a wide range of applications including construction of huge metal structures but not in Mauritius. There is, therefore, much scope for the use of weathering steel in the island. The metal, however, needs to be tested through outdoor atmospheric exposures first before being imported and used on a large scale. It is difficult to know how weathering steel would behave in Mauritius, being a tropical island without any experimentation. Also, the benefits that can be obtained with the metal need to be carefully investigated.

1.1. Aims and Objectives

This study will, therefore, aim to propose weathering steels as a sustainable alternative to the commonly used carbon steels in Mauritius. This is expected to lead to the commercialization of this product in Mauritius with the aim of having a more sustainable future in the island.

The objectives of this project were, therefore:

- To find how low carbon steel is used in Mauritius and the corrosion problems associated with carbon steel in Industry and to work on a Life Cycle Assessment for carbon steel in Mauritius.
- To determine how weathering steel corrodes in the Mauritian atmosphere as compared to carbon steel.
- To determine the feasibility of using weathering steel in Mauritius by considering the factors, including economic and environmental issues, on which the use of the metal will depend.

The aims were fulfilled through:

- Working out the life cycle assessment of steels in Mauritius.
- Performing outdoor exposures of weathering steel and determining its mass loss and its atmospheric corrosion behaviour using other techniques such as SEM and x-ray diffraction (to determine the mechanism of the corrosion reaction).
- Analysing the cost effectiveness, economically and environmentally, of using weathering steels in Mauritius instead of carbon steels.

After determining the corrosion behaviour of weathering steel in Mauritius at different sites, the economic and environmental advantage of using weathering steel in Mauritius were quantified and compared to the low carbon steel through the LCA performed. It should be noted that weathering steel has an improved performance over low carbon steel, especially in relation to corrosion resistance. This will have a consequent impact on maintenance costs and the lifetime of the structure. To be able to quantify this impact, in terms of actual cost, it is essential to determine the improvement in corrosion loss of weathering steel over low carbon steel. It is through this data that the viability of the use of weathering steel was determined through a cost analysis. This was coupled with any environmental impact that the weathering steel would incur. Hence, the feasibility of importing and using weathering steel in Mauritius was determined.

It is worth noting that a positive result in this study can lead to:

- The introduction and commercialization of this product in Mauritius.
- Savings in the long term, being a corrosion resistant type of steel.
- Uses in the manufacture of sustainable systems such as solar water heaters and other structures.

2. LITERATURE SURVEY

In a bid to meet the aims and objectives of this project, a literature survey was performed on weathering steel together with its corrosion behaviour and the methodology to build up a life cycle assessment for steel.

2.1. Weathering Steel

Weathering steel is a high strength low alloy steel, containing alloying elements, mainly chromium, copper, phosphorus and nickel, and has a superior corrosion resistance compared to carbon steel. On exposure, a protective oxide film known as the 'patina' is formed on the surface that strongly inhibits the corrosion process (Heckroodt, 2002). The patina on weathering steel not only offers greater corrosion resistance, but is also responsible for its attractive appearance and self-healing abilities (Morcillo et al., 2013).

2.1.1. Protective Layer Formation

In the presence of moisture, steel and oxygen combines to form rust. On most carbon steels, the rust forms a loose crystalline structure therefore more water and air is allowed to attack deeper into the steel. It forms even more rust and weakens the base metal.

On the other hand, weathering steel in its bare and mature state has a protective oxide coating (patina) which is about the same thickness as a heavy coat of paint. This protective oxide film develop under condition of alternate wetting and drying and adheres tightly to weathering steel in fine, dense grains that are relatively impervious to further atmospheric corrosion, thereby sealing the base metal from the air and further corrosion.

Figure 1 shows the difference between the corrosion of carbon steel and weathering steel.
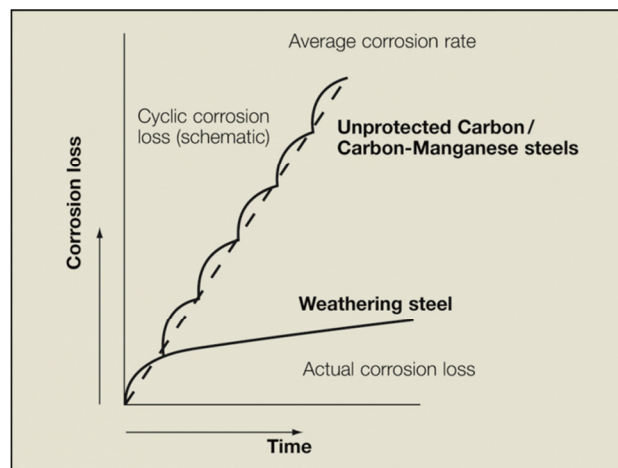
Figure 1: Corrosion loss of carbon and weathering steels (SteelConstruction.info)

The protective oxide film has different colours than the rust on other carbon steels, ranging from a dark reddish-brown to purple grey, depending on the age of the structure, the pollutants in the air, local weather conditions, or the location of the steel within the structure (McDad et al., 2000) as shown in figure 2.
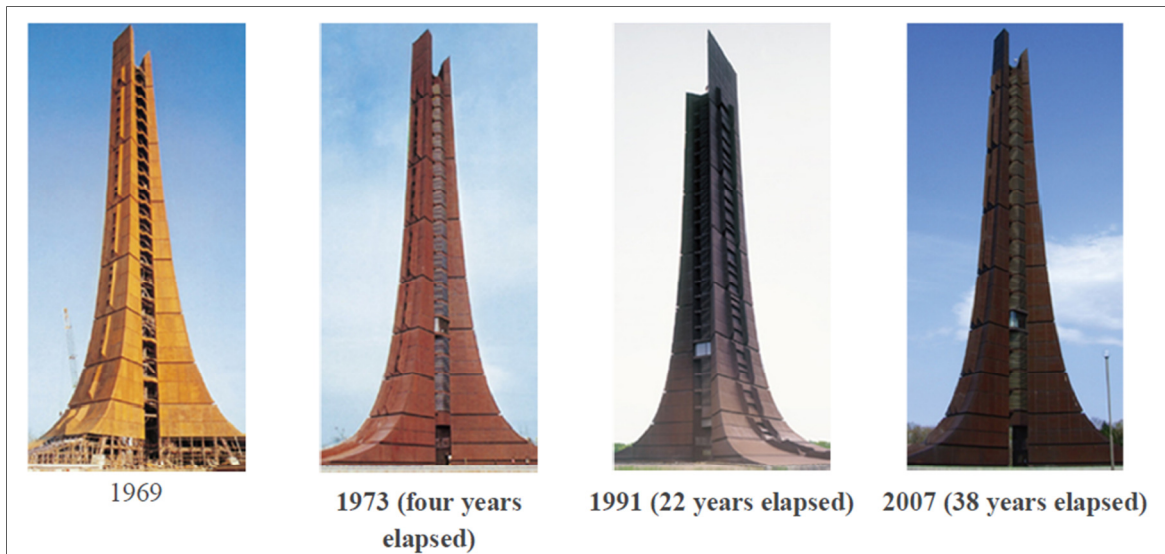
Figure 2: Hokkaido Centennial Memorial Tower in Japan (made of weathering steel)

The degree of exposure has a strong influence on the weathering process. Steel exposed to rain, sun, and wind weathers more quickly than steel in a sheltered location. On sheltered surfaces, the oxide tends to be rougher, less dense and less uniform.

Frequent wet-dry cycles caused by rainfall and/or dew, followed by wind and sun, are important factors affecting protective oxide film formation. In moderate industrial environments, weathering steel usually matures most rapidly and achieves the darkest tone. In rural locations, the protective oxide film develops more slowly and generally has a lighter tone.

2.1.2.   Corrosion Products of Weathering Steel

The main phases of rust are different oxy-hydroxides as α- FeOOH (goethite), β-FeOOH (akaganeite) and γ-FeOOH (lepidocrocite) and some spinel type of iron oxides such as magnetite Fe_3O_4 which are contained in the rust layer depending on environmental condition (Lien and Hong, 2013). The constituents of the rust layer on weathering steel vary depending on the atmospheric exposure periods from lepidocrocite (γ-FeOOH) – (less than a few years) to an X-ray amorphous substances (several years) and finally to a goethite (α-FeOOH) – (decades).

The goethite-type phase forms due to the concentration of Cr and the substitution of Cr for Fe in the goethite structure. Since the X-ray amorphous substance does not show a well-defined Bragg peak on the X-ray diffraction spectrum, it is considered to consist of ultrafine particles of FeOOH. (Konishi et al., 2006)

The Cr content in the protective rust layer is approximately 4% by mass. The protective rust possess the structure of α-(Fe$_{1-x}$, Cr$_x$) OOH, which is called Cr-goethite. The corrosion rate of weathering steel decreases as the X-ray amorphous substance forms and matures into the goethite phase. The protective rust layer of weathering steel consists of a large amount of Cr-goethite after long-term exposure.

Studies by various spectroscopic methods revealed that the protective rust layer has a double-layer structure. The inner layer consists mainly of ultrafine particles of Cr-goethite and has a densely packed texture with a few cracks or pinholes. The protective ability is derived from the characteristic texture of the rust layer which acts as a physical barrier against corrosive ions and/or water.

The composition ratio of the protective rust layer of weathering steel correlates with its protective ability. The chemical reactivity and electric conductivity of goethite are lower than those of other corrosion products. Therefore, the α / γ^* ratio, where α is the mass of goethite and γ^* is the sum of the masses of akaganeite (β-FeOOH), lepidocrocite (γ-FeOOH) and magnetite (Fe$_3$O$_4$), can be used to estimate the protective ability of the rust layer. As the α / γ^* ratio becomes larger, the corrosion rate decreases. Such a rust layer appears dense and continuous. In a saline environment, the mass ratio of goethite to akaganeite, α / β, also corresponds well to the protective ability.

Cr-goethite with Cr content greater than about 3% by mass possesses cation selectivity that prevents the penetration of aggressive corrosive anions such as chloride ions. This property of Cr-goethite is thought to provide electrochemical protection to the rust layer (Konishi et al., 2006).

Figure 3 illustrates the SEM micrographs of the oxy-hydroxides where fine plates ("flowery" structures) (A-B) are typical of lepidocrocite, globular (cotton balls) (C) and fine whiskers (D) are typical of goethite, and "cotton balls" (E) and cigar-shaped crystals (F) are typical of akaganeite. (Morcillo et al., 2011)
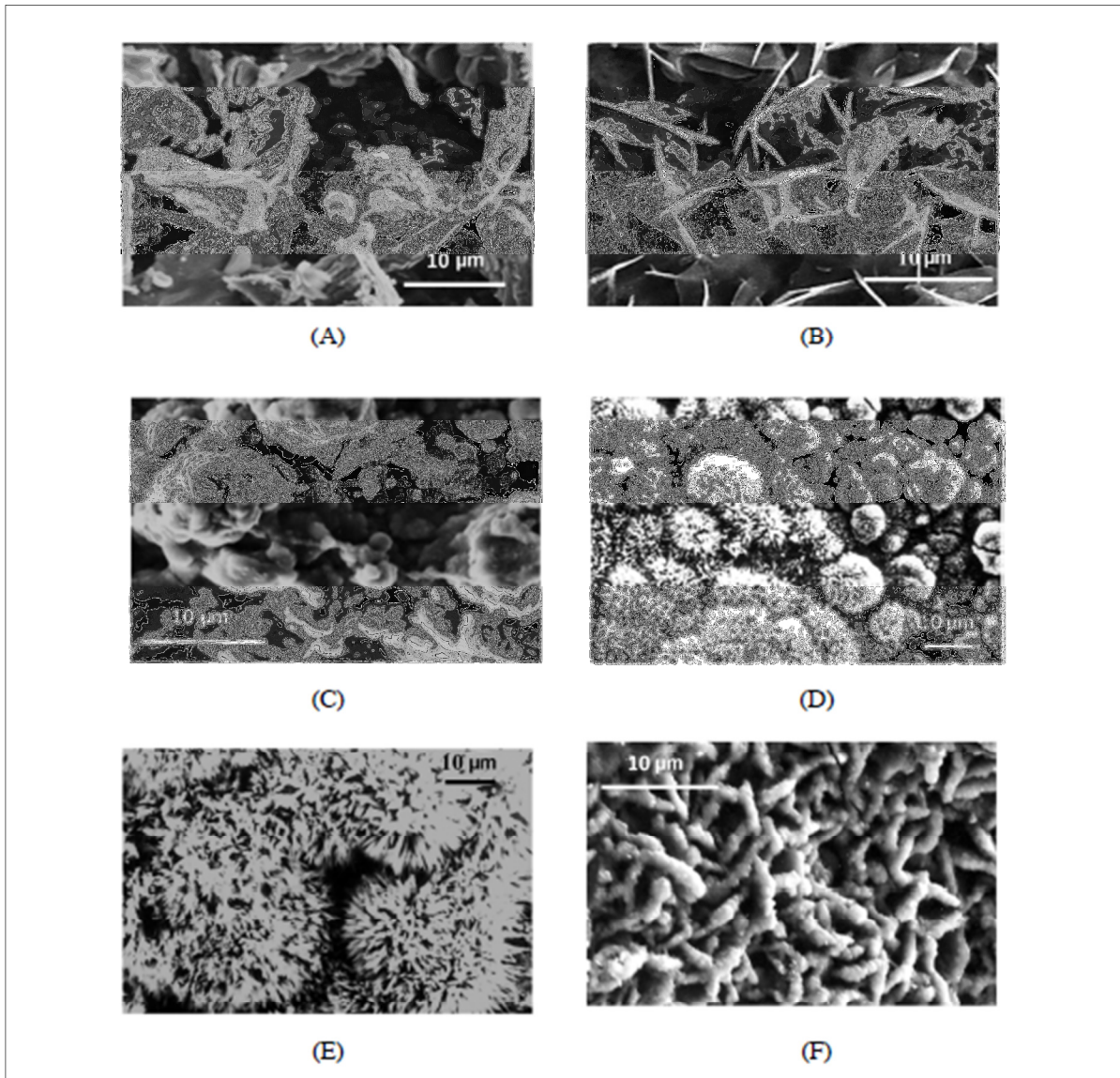
Figure 3: SEM micrographs of rust products

2.1.3. Benefits of Weathering Steels

Weathering steel has many advantages such as (Corus construction and industrial, 2016):

- **Low Maintenance**

Periodic inspection and cleaning should be the only maintenance required to ensure the bridge continues to perform satisfactorily. Hence, weathering steel bridges are ideal where access is

difficult or dangerous, and where future disruption needs to be minimized. Minor damage to this oxide film heals itself. Therefore, maintenance is greatly reduced compared to a painted bridge. Bare weathering steel is suitable for many atmospheric environments, including moderate industrial and some marine exposures.

- **Cost Benefits**

Weathering steel is slightly more expensive than ordinary structural steel however since little or no initial painting or subsequent repainting is required, weathering steel results in significant first cost and life-cycle cost savings. In painted applications of weathering steel, the number of times that repainting is required is reduced since even when corrosion occurs in the base metal due to defects in painted film, corrosion progresses slowly hence reducing blistering and peeling of the paint film (Nippon Steel and Sumitomo Metals, 2016). Typically, the costs of weathering steel bridges are approximately 5% lower than conventional painted steel alternatives (Materials, 2016). The minimal future maintenance requirements of weathering steel bridges greatly reduces both the direct costs of the maintenance operations, and the indirect costs of traffic delays or rail possessions.

- **Attractive appearance**

The attractive appearance of unpainted mature weathering steel bridges and structures demonstrates excellent aesthetic properties by blending pleasingly with the environment and improves with age. Weathering steel is also used in painted applications

- **Environmental benefits**

The environmental problems associated with paint Volatile Organic Compound emissions, and the disposal of blast cleaning debris from future maintenance works are avoided.

- **Safety benefits**

Health and safety issues relating to initial painting are avoided, and the risks associated with future maintenance are minimized.

- **Weldability and Workability**

While trace amounts of alloying elements are such as copper and chromate are added to weathering steel to ensure high weather resistance, the carbon content is lowered to provide appropriate weldability. It also possesses workability similar to ordinary steel of same strength.

2.1.4. Limitations of Weathering Steel

There are certain environments which can lead to durability problems. The performance of weathering steel is not satisfactory in the following environments:

- **Marine Environment**

Sea water spray, salt fogs or coastal airborne salts contain high concentrations of chloride ions. Since salt has the ability to attract and hold water molecules from the surrounding environment, it has adverse effects on the patina as it maintains a continuously damp environment on the metal surface. Generally, weathering steel should not be used within locations exceeding the salinity classification of S2 (Cl < 300mg/m2/day) according to ISO 9223 therefore caution is required when considering use within 2 km of a coast (Low and Sandeford, 2013).

- **Continuously wet/damp conditions**

For the adherent patina to form, alternate wet/dry cycles are required. In continuously wet or damp conditions, the corrosion rate of weathering steel will be similar to that of ordinary structural steel. Examples include weathering steel elements submerged in water, buried in soil or covered by vegetation. If weathering steel is used in such cases, it should be painted and the paint should extend above the level of the water, soil or vegetation (Corus Construction and Industrial, 2016).

- **Atmospheric Pollution**

Atmospheres containing high concentrations of corrosive chemicals or industrial fumes such as SO_2 are not suitable for the use of weathering steel. It should not be used in environments with a pollution classification above P3 to EN ISO 9223 (i.e. $SO_2 > 200$mg/m^2/day). However, this classification level is rarely encountered nowadays since there are limits on industrial pollution of the atmosphere. Diesel fumes contain airborne sulphur compounds but when they are within limits they actually have a beneficial effect in forming insoluble corrosion products by reacting with the alloying elements in the steel. Moreover, the slightly oily nature of the deposits from diesel exhaust fumes may also act as a barrier to water and reduce corrosion of the steel.

2.1.5. Previous Studies on Corrosion of Weathering Steel

Weathering steel evolved since the 1930's when United States Steel Corporation acquired various patents for high-strength low-alloy steel products (Crampton *et al.*, 2013). It was first used in the construction of steel bridges in 1964 and by mid-1980's, around 2000 weathering steel bridges had been constructed in the United States. A survey on 49 of the bridges in seven different states, at that time, revealed that their performance was "good" (Crampton *et al.*, 2013).

It should be noted that though all the bridges were not erected in marine environments, many of them resisted the corrosive effects of de-icing salts. Consequently, weathering steel is also considered as an atmospheric corrosion resistant steel (Coomarasamy *et al.*, 2008).

Recent atmospheric corrosion exposures of weathering steel and mild steel have shown a significantly lower atmospheric corrosion rate of the former. In a study performed by Dong *et al.* (2007) at several sites in China, including a range of different types of atmospheres, it was observed that the degradation of the two metals followed the power law ($C = At^n$) where n for weathering steel samples was at least half of that of mild steel.

Factors that have been reported to affect the corrosion resistance of weathering steel are (Morcillo *et al.*, 2013):

- Whether the samples are sheltered are not. Sheltered samples have shown higher corrosion losses and the development of severe pitting. This was attributed to the washing action of rain removing the airborne contaminants. Taking into consideration the high amount of rainfall in Mauritius, the corrosion rate of weathering steel, for outdoor exposure, can therefore be expected to be low;
- Time of wetness- Humid atmospheres decrease the corrosion resistance of weathering steel;
- Airborne pollutants and salinity and de-icing salts- The level of airborne pollutants and salinity has been found to be low in Mauritius and de-icing salts are not used. Therefore, these factors are not expected to significantly affect the corrosion of weathering steel in Mauritius.

In 2013, a study by Lien and Hong concluded that the initial corrosion rate of weathering steel exposed at Hanoi (urban site) was very high, however it reduced with exposure-time due to the formation of corrosion product on the sample surface. In first year the corrosion rate of weathering steel at Hanoi is similar to that of carbon steel, and then it decreased faster and becomes lower in comparison with carbon steel. The same experiment was done at Donghoi (marine site) and it was observed that corrosion rate of weathering steel was always smaller than that of carbon steel. On possible explanation was the faster formation of protective layer contained ion of Cu and Cr on weathering steel samples exposed to Donghoi which was perhaps promoted by high humidity.

X-ray diffraction and Micro Raman Analysis of the rust detected that alloyed elements such as Cr and Cu in the rust formed in the early stage of exposure (1 - 7 days) which were found to be rich in the inner layer of rust.

The main compounds of rust formed on weathering steel exposed to Hanoi and Donghoi are *α-*

FeOOH (goethite), β- FeOOH (akaganeite) and γ-FeOOH (lepidocrocite). Among them lepidocrocite is dominant and was detected on all tested samples. The dense α-FeOOH phase appeared very soon-just after one day exposure at Donghoi and after three days at Hanoi, in addition, the insoluble copper hydroxyl-sulphates were also detected in the rust.

Jaén et al. also found that the dominant phases after short-term exposure were amorphous or crystalline oxyhydroxides such as lepidocrocite (γ-FeOOH) and goethite (α-FeOOH). Maghemite (γ-Fe_2O_3) and magnetite (Fe_3O_4) were also found. Akaganeite (β-FeOOH) was identified as prominent component in the most aggressive conditions, with high chlorine amounts, and occluded within the rust.

2.2. Life Cycle Assessment (LCA)

Life Cycle Assessment is a tool to assess the environmental impacts and resources used throughout a product's life cycle, i.e., from raw material acquisition, via production and use phases, to waste management (Finnveden et al., 2009). For each stage of a product's life cycle, a determination is made of the use of natural resources and emissions to land, water and air. It takes into consideration the product's environmental impact from "Cradle to Grave". Steel in products has a unique characteristic: it can be recycled into steel scrap, time and again, to serve as the raw material for new steel. LCA also covers recycling when the product's useful life has come to an end or where it is used as the raw material for a new product (Sperle, J et al., 2013).

Complying with ISO 14040: 2006- Environmental management- Life Cycle Assessment- Principles and Framework, the life cycle assessment (LCA) consists of four steps namely;
  i.   Goal and Scope of study- it encompasses the purpose for this study with the functional unit, boundary system, data sources and assumptions.
  ii.   Life Cycle Inventory- It consists of the data collection and calculation of relevant inputs and outputs.
  iii. Life Cycle Impact Assessment- It evaluates the environmental impacts assigned to the life cycle inventory.
  iv.   Interpretation- The results of the impact assessment are analysed in line with the goal and scope of the study.

Figure 4 illustrates the framework of the LCA.
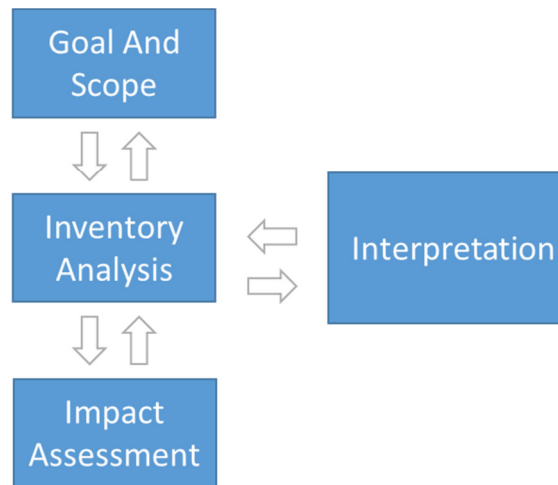
Figure 4: Framework of LCA (ISO 14040*)***

2.2.1. Scope and goals of study

- **Functional Unit**

The functions of the system being studied are clearly specified. The functional unit is a quantified performance of a product system for use as a reference unit in a life cycle assessment study The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related (ISO14040: 197(E)).

- **System Boundaries**

The system boundaries determine which unit processes shall be included within the LCA. Several factors determine the system boundaries, including the intended application of the study, the assumptions made, cut-off criteria, data and cost constraints, and the intended audience (ISO14040: 197(E)).

Boundaries between the technological system and nature

A life cycle usually begins at the extraction point of raw materials and energy carriers from nature. Final stages normally include waste generation and/or heat production.

Geographical area

Geography plays a crucial role in most LCA studies, e.g. infrastructures, such as electricity production, waste management and transport systems, vary from one region to another. Moreover, ecosystems sensitivity to environmental impacts differs regionally too.

Time horizon

Boundaries must be set not only in space, but also in time. Basically LCAs are carried out to evaluate present impacts and predict future scenarios. Limitations to time boundaries are given by technologies involved, pollutants lifespan, etc.

Boundaries between the current life cycle and related life cycles of other technical systems

Most activities are interrelated, and therefore must be isolated from each other for further study. For example production of capital goods, economic feasibility of new and more environmentally friendly processes can be evaluated in comparison with currently used technology (Tillman et al., 1993).

Examples of system boundaries include (Worldsteel LCA Methodology Report, 2011):

Cradle-to-gate
Cradle-to-gate LCI study with and without the end-of-life recycling of the steel covers all of the production steps from raw materials in the earth (i.e. the cradle) to finished products ready to be shipped from the steelworks (i.e. the gate). The cradle-to-gate LCI study, with end-of-life recycling, includes net credits associated with recycling the steel from the final products at the end-of-life (end-of-life scrap). It does not include the manufacture of the downstream final products or their use.

Gate-to-gate
The gate-to-gate level model consists of all the steelmaking processes (process chain) as well as any additional on-site ancillary services that are required. This includes boilers, compressors, wastewater treatment, etc. It does not include upstream processes (raw material inputs) and substitution, waste treatment, etc.

2.2.2.   *Inventory*

Next, the inventory is produced. Energy and raw material requirements and environmental emissions of the product, process or activity are quantified. Totals are presented for all stages of production, from raw material acquisition to waste management.

- **Raw material and energy**

Examples of raw materials are iron ore, carbon (C), coke, ferrochrome (FeCr), ferronickel (FeNi), ferrosilicon (FeSi), and ferromanganese (FeMn). Examples of input goods are welding

wire, chemicals such as sodium hydroxide (lye), lime, and calcium oxide.

Iron ore

Iron ore is delivered to the steelmaking plants either in the form of iron ore fines or in the form of pellet. This depends on the quality of the original ore material and on the operational practices at the steelmaking plants. Pelletising is performed on very fine ores to ensure satisfactory gas permeability in the blast furnace. Similarly, iron ore fines are sintered to obtain an agglomerated product, called "graded sinter", of suitable size, porosity and strength for charging into a blast furnace.

Ferrous Scrap

Scrap input to the steelmaking process can be in the form of internal scrap, home scrap or external scrap. For scrap coming from an external supply, the environmental burdens associated with the transport from the scrap merchant, municipal facilities or other factories to the steelworks is included, although this is generally negligible (Worldsteel LCA Methodology Report, 2011).

Fuels

Examples of fuels are coal, coke, natural gas, LPG and oil. Where fuels are concerned, data is required relating to the production and transportation of the fuel as well as the emissions that arise when the fuel undergoes combustion in the specific process.

- **Transport of raw materials**

Where data for transport journeys in respect of raw materials, chemicals and other input goods used in steel production is concerned, the relevant freight carrier is specified e.g. truck, ship or train as well as total weight, maximum load capacity and fuel. In the analysis are included the distance for transport of raw materials to the steel plant as well as possible transport of steel slabs, where rolling is carried out at another geographical location (Sperle, J et al., 2013).

- **Steel Manufacturing**

Steel production involves several processing stages including ironmaking, primary and secondary steelmaking, casting and hot rolling. These are followed by some of the following fabrication processes: cold rolling, annealing, tempering, coating and/or heat treatment. Steels can be made either from raw materials (e.g. iron ore, coal and limestone) or by recycling steel

scrap (Worldsteel LCA Methodology Report, 2011).

- **Consumption of energy and input goods**

For fabrication of the structure, electric power is used for e.g. processing and welding, fuel for hardening and so on. The same approach should be adopted for consumption of the input goods. This may mean that differing amounts of welding wire are used or material required in one case and not in the other. Examples of input goods are welding wire and chemicals e.g. for surface treatment.

When the amounts of energy and input goods are known and data for the production of these has been prepared, it is possible to estimate the environmental impact for fabrication of the structure (Sperle, J et al., 2013).

- **Use of steel structures**

Passive Structures

A passive steel structure often has insignificant environmental impact or none at all, during the utilisation phase. Environmental benefits for passive structures are therefore mainly related to the consumption of lesser amounts of steel as well as a lesser amount of steel needing to be transported. Examples of passive structures include Cisterns, tanks, process systems, shelves and furniture.

Active Structures

For active steel structures such as vehicles, about 90 per cent of the avoided environmental impact is related to the use phase (Sperle, J et al., 2013).

- **Recycling of steel structure**

Steel is completely recyclable. Therefore, it is important to consider recycling in LCA studies involving steel, namely the steel scrap that is recycled from a final product at the end of its life. In addition, steel is a vital input to the steelmaking process, and this input of steel scrap should also be considered in LCA studies (Worldsteel LCA Methodology Report, 2011).

It is necessary to assess how much of the steel in the structure can be recirculated as steel scrap when the structure has reached the end of its useful life.

2.2.3. Impact Assessment

The impact assessment phase of an LCA assigns the results of the inventory to different impact

categories. Steel production is an energy-intensive industry. The consumption of energy and electricity are one of the main contributors to the environmental impact of the steelmaking process. Therefore, its influence on the LCIA of the product is obviously very much dependent on the location of the steel works, which will often determine the source of electricity and energy consumption (Worldsteel LCA Methodology Report, 2011).

2.2.4. *Improvement Analysis*

The improvement analysis component of LCA is a systematic evaluation of the need and opportunities to reduce the environmental burden associated with energy and raw material use and waste emissions throughout the life cycle of steel (Liu and Liptak, 1997).

3. METHODOLOGY AND TECHNICAL INFORMATION

To study the atmospheric corrosion behaviour of weathering steel in Mauritius, the metal samples was exposed outdoors about 1 year, at two different sites. Ideally the sites were located at Port Louis, the capital city, which would consist of an industrial marine atmosphere, and at Reduit, which represented the rest of the country.

In fact, the atmospheric corrosivity of the Mauritian atmosphere falls in category C3 (moderate) to C4 (severe) according to ISO 9223 (Surnam, 2010). Based on this study, apart from Port Louis, the other sites considered in Table 1 were found to fall in category C3. Hence, it is expected that most of the regions in Mauritius would have a corrosivity category of C3. Port Louis, on the other hand, has corrosivity category C4.

Hence, weathering steel was exposed outdoors at Port Louis and Reduit so as to obtain a good insight on the corrosion behaviour of weathering steel in Mauritius. Low carbon steel samples were also exposed for comparison purposes. Simultaneously, airborne salinity and sulphur dioxide content in the atmosphere were monitored through the wet candle method and the lead dioxide cylinder respectively. The results were used to investigate how the metals corrode in the atmosphere. A model for the corrosion loss of the weathering steel and low carbon steel was developed for each site and the results were compared.

With such an important quantity of steel being used on the island, a life cycle assessment was performed to understand the environmental impacts that were being incurred due to the consumption of steel, ranging from its production to its recycling. Furthermore, this LCA was conducted to provide a better insight of using weathering steel as an alternative material.

Table 1: Environmental parameters for various sites in Mauritius (Surnam, 2010)

Site	Average chloride deposition rate ($mg/m^2.d$)	Chloride class according to ISO 9223	Sulphur dioxide concentration level ($\mu g/cm^3$)	SO_2 class according to ISO 9223	Ttime of wetness per year (hrs)	Time of wetness class according to ISO 9223	Corosivity category
Port Louis	6.8	S_1	3.7	P_0	1957	T_3	2-3
St Julien d'Hotman	2.3	S_0	>2.6	P_0	6723	T_5	4
Belle Mare	5.3	S_1	>2.6	P_0	3634	T_4	3
Reduit	5.9	S_1	14.7	P_1	7781	T_5	4
Palmar	2.3	S_0	>2.6	P_0	4916	T_4	3
Vacoas	2.3	S_0	14.7	P_1	5891	T_5	4

3.1. Outdoor Exposure of Carbon and Weathering Steels

Prior to exposure, both metal specimens, carbon and weathering steels, had to be cleaned since the surface of the metals was initially covered with a thin layer of rust.

3.1.1. Surface Preparation of Metal Specimens

Samples were cleaned and prepared for exposure according to standard practice ASTM G1 (1999). The following procedures were carried out to obtain a clean and even surface (Dibble. K., n.d.). Firstly, the specimens were immersed in 10% concentrated sodium hydroxide (NaOH) for 5 minutes to remove all polar substances such as fats and oils so that a hydrophilic and inorganic surface remains, ensuring an effective acid clean as in Figure 5.

Figure 5: Cleaning in 10% sodium hydroxide

They were then rinsed under high flow of water to wash away the alkali and other residual substances, followed by, the specimens being immersed in 10% concentrated hydrochloric acid (HCl) for 4 hours to remove ionic deposits from the metals. After the acid stage, the specimens were rinsed to remove any loose debris or sludge as well as removing residual chemical.

Figure 6 shows the cleaning of the metal sample in hydrochloric acid.
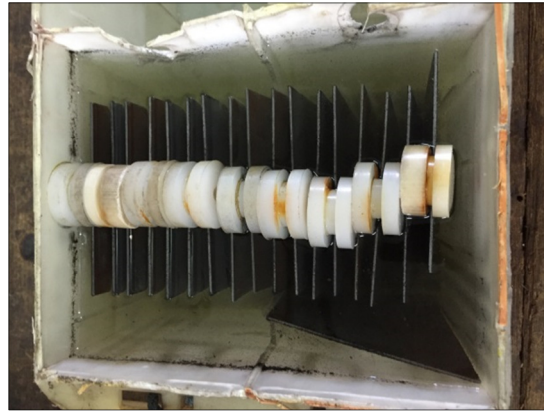
Figure 6: Cleaning in 10% concentrated HCl acid

Since after the acid cleaning, the metals were highly susceptible to corrosion due to the destruction of the passive layer, the specimens were immersed in 10% concentrated sodium hydroxide solution for 5 minutes to neutralize the acid. Compressed air was used to remove any loose debris from the metal surface as in Figure 7 and the specimens were then dried using heated air from a specimen dryer as illustrated in Figure 8.

Figure 7: Cleaning with compressed air
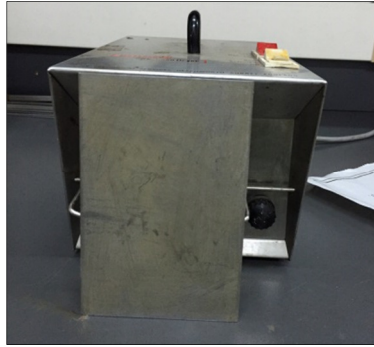
Figure 8: Drying of samples

Figures 9 and 10 show unclean and cleaned specimens of both weathering and carbon steel respectively.
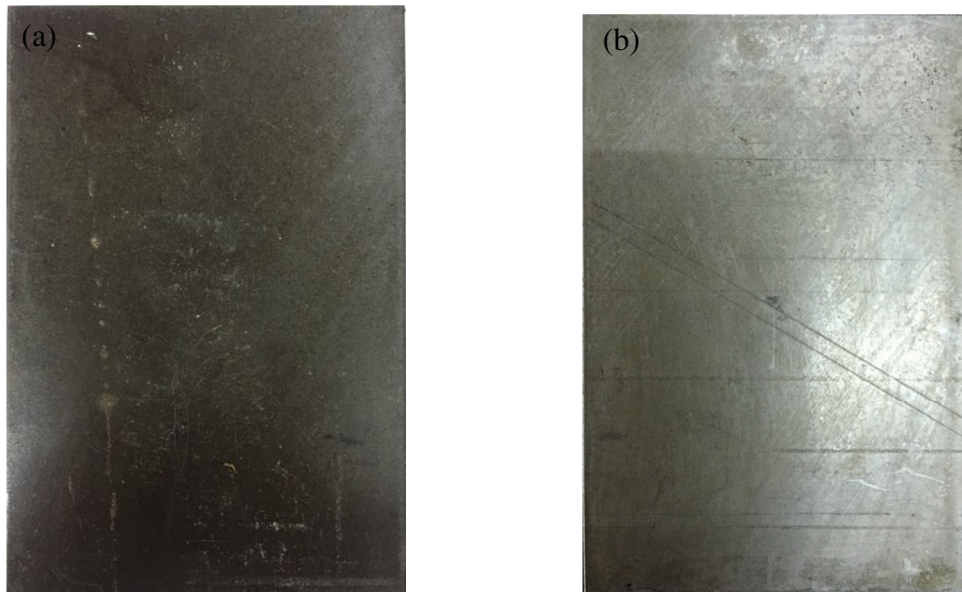
Figure 9: Weathering steel (a) Before cleaning (b) After cleaning
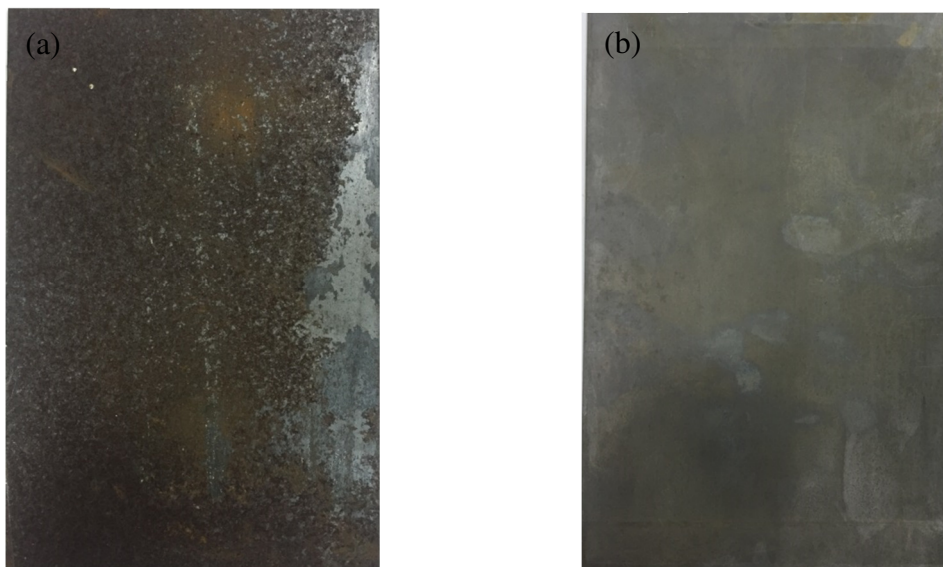
Figure 10: Carbon Steel (a) Before Cleaning (b) After Cleaning

After cleaning the metal specimens, they were marked by stencilling using hardened steel stencil stamps hit with a hammer. Mild steel specimens and weathering steel specimens to be exposed at Réduit were marked using the designation 'CR' and 'WR' respectively. Mild steel specimens and weathering steel specimens to be exposed at Port Louis (Bulk Sugar Terminal) were marked using the designation 'CP' and 'WP' respectively.
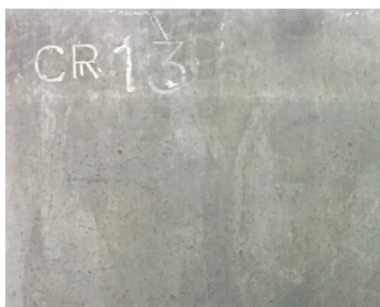
Figure 11: Marked metal specimen

Finally, the dimensions of the metal specimens were measured using a digital Vernier calliper and they were weighed using an electronic balance. The specimens were then stored in a desiccator using silica gel as desiccant.

3.1.2.   Chemical Composition of Metal Samples

The chemical composition of both carbon and weathering steel was assessed and tabulated below.

Table 2: Chemical composition of steels

Steels	Alloying Elements (wt. %)								
	C	Si	Mn	S	P	Cu	C	Cr	Ni
Carbon Steel									
Weathering Steel									

3.1.3. Exposure of Metal Samples

The metal samples at both locations were exposed on galvanised and painted exposure frames made of mild steel, according to BS EN ISO 8565. They were used to hold the samples at an angle of 45^0 from the horizontal, as shown below.
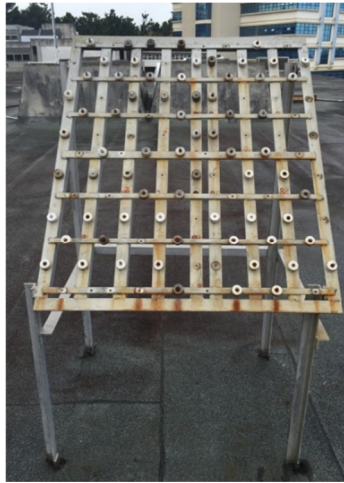
Figure 12: Exposure frame

Specimen holders were made using nylon rod to prevent galvanic corrosion. Grooves were made on the nylon rod using a CNC machine and it was then centre drilled on a lathe and separated into individual nylon supports.

Figure 13: Manufacturing of nylon supports

Figure 14: Nylon supports

The date and time of exposure of the samples at each site is recorded in the table below

Table 3: Date and time of exposure

Site	Date	Time
Reduit	10-Aug-16	12:00
Port Louis (Bulk Sugar Terminal)	22-Aug-16	11:00

3.1.4.   Collection of Metal Samples

Four samples of carbon and weathering steels were collected after an exposure time of 3, 6, 10 and 13 months respectively from both site locations. Three from which were cleaned according to ISO 8407 while the remaining one was kept for morphology analysis of rust on the samples.

Aftermath removal of rust, the weight loss of the samples were obtained and the corresponding thickness reduction were calculated.

Table 4 shows the details on the collection of samples.

Table 4: Date and time of collection of samples

Collected Specimens	Site	Date	Time
First batch-3 months	Reduit	10-Nov-16	11:00
	Port louis	9-Dec-16	10:30
Second batch-6 months	Reduit	13-Feb-17	10:00
	Port louis	15-Feb-17	10:00
Third batch-10 months	Reduit	29-Jun-17	10:30
	Port louis	22-Jul-17	10:30
Fourth batch-13 months	Reduit	11-Sept-17	9:30
	Port louis	27-Sept-17	10:00

3.1.5.   Cleaning of Metal Samples after Exposure

Prior to cleaning, the mass of the corroded samples were recorded using an electronic balance to observe the mass gain due to oxidation, as shown in figure below.

Figure 15: Mass recording of corroded samples

The metal samples were cleaned according to ISO 8407 (2009), Table 5 shows the reagents used for the cleaning solution, the total time the samples were immersed in it and the temperature of the solution.

Table 5: Chemical and conditions for acid solution

Chemical Products	Total time	Temperature
500 mL of hydrochloric acid (ρ = 1.19 g/mL)		
3.5 g of hexamethylenetetramine	10 min	20 °C to 25 °C
Distilled water to make 1000 mL		

Figure 16 shows a sample being cleaned in the acid solution.
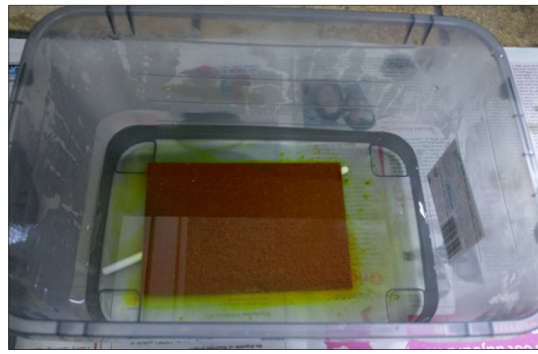
Figure 16: Cleaning of corroded samples

After cleaning, the sample was washed with water. A non-metallic brush was used to scrap off the stubborn rust particle. The mass of the cleaned samples were weighed using the same electronic balance. Moreover, unexposed similar metal samples of carbon steel and weathering steel were cleaned using the same procedure to obtain the mass loss of base metal and it was used as correction to obtain the mass loss of the exposed sample due to corrosion only.

3.1.6. Mass Loss and Thickness Reduction Calculations

3.1.6.1. Mass loss of Control Samples

Table 6 shows the mass loss of the control samples (unexposed samples).

Table 6: Mass loss of control samples

Specimen	Mass before cleaning (g)	Mass after cleaning (g)	Mass loss (g)
Mild Steel	167.764	167.524	0.239
Weathering Steel	228.553	228.425	0.128

The mass loss were calculated as follows.

$$Mass\ loss\ of\ control\ samples = M_{bc} - M_{ac} \qquad (1)$$

Where M_{bc} is the mass of control samples before cleaning (g)
M_{ac} is the mass of control samples after cleaning (g)

3.1.6.2. *Mass loss of Exposed Samples*

The mass loss of each sample were calculated as follows.

$$Mass\ loss\ of\ exposed\ samples = M_{be} - M_{ae} \qquad (2)$$

Where M_{be} is the mass of cleaned samples before exposure (g)
M_{ae} is the mass of cleaned samples after exposure (g)

To obtain the correct mass loss of the specific samples, the following calculation were performed.

$$Corrected\ mass\ loss\ for\ carbon\ steel = m_c - m_{cc} \qquad (3)$$

$$Corrected\ mass\ loss\ for\ weathering\ steel = m_w - m_{wc} \qquad (4)$$

Where m_c is the mass loss of carbon steel (g)
m_{cc} is the mass loss of the control samples of carbon steel (g)
m_w is the mass loss of weathering steel (g)
m_{wc} is the mass loss of the control samples of weathering steel (g)

The mass, mass loss and corrected mass of the exposed samples are shown in Tables 7 and 8.

Table 7: Samples exposed at Reduit

Specimen	Mass before exposure (g)	Mass after exposure(g)		Mass loss (g)	Corrected Mass loss (g)
		Mass before cleaning (g)	Mass after cleaning (g)		
3 months					
CR1	171.269	172.761	168.851	2.418	2.179
CR2	168.840	170.322	166.622	2.218	1.979
CR3	171.177	172.683	168.813	2.364	2.125
WR1	230.182	231.683	227.461	2.721	2.593
WR2	230.574	231.858	228.271	2.303	2.175
WR3	227.228	228.719	224.684	2.544	2.416
6 months					
CR5	171.378	173.518	167.149	4.229	3.990
CR6	171.846	173.996	167.578	4.268	4.029
CR7	172.228	174.492	167.752	4.476	4.237
WR5	226.933	228.981	224.043	2.890	2.762
WR6	230.986	233.131	227.490	3.496	3.368
WR7	231.298	233.454	227.925	3.373	3.245
10 months					
CR9	171.490	174.328	165.140	6.350	6.110
CR10	169.172	172.005	163.290	5.882	5.642
CR11	171.410	174.042	165.238	6.172	5.933
WR9	229.758	232.211	225.725	4.033	3.905
WR10	232.183	234.741	227.824	4.359	4.231
WR11	230.993	233.528	226.762	4.231	4.103
13 months					
CR13	169.970	173.233	163.117	6.853	6.614
CR14	171.170	174.391	164.302	6.868	6.628
CR15	171.913	174.953	165.203	6.710	6.471
WR13	228.614	231.590	223.819	4.795	4.667
WR14	227.092	230.158	222.674	4.418	4.290
WR15	232.241	234.222	227.734	4.507	4.379

Table 8: Samples exposed at Port Louis (Bulk Sugar Terminal)

Specimen	Mass before exposure (g)	Mass after exposure(g)		Mass loss (g)	Corrected Mass loss (g)
		Mass before cleaning (g)	Mass after cleaning (g)		
3 months					
CP1	172.636	173.840	170.359	2.277	2.038
CP2	166.091	167.422	163.820	2.271	2.032
CP3	170.746	172.077	168.330	2.416	2.177
WP1	229.338	230.248	227.606	1.732	1.604
WP2	228.799	230.122	226.638	2.161	2.033
WP3	230.282	231.436	228.162	2.120	1.992
6 months					
CP5	171.221	173.813	167.087	4.134	3.894
CP6	171.426	174.170	166.066	5.360	5.121
CP7	171.704	174.300	166.805	4.899	4.660
WP5	231.614	233.911	228.173	3.441	3.313
WP6	231.390	233.716	227.039	4.351	4.223
WP7	229.306	231.849	225.117	4.189	4.061
10 months					
CP9	171.062	172.446	164.022	7.040	6.801
CP10	171.740	173.026	164.999	6.741	6.502
CP11	170.666	172.341	164.186	6.480	6.241
WP9	230.376	232.784	225.784	4.592	4.464
WP10	228.842	231.312	223.998	4.844	4.716
WP11	230.166	232.434	225.644	4.522	4.394
13 months					
CP13	174.113	175.425	166.301	7.81	7.572
CP14	170.504	171.908	162.862	7.642	7.403
CP15	171.118	172.424	163.010	8.108	7.869
WP13	228.184	230.692	223.079	5.105	4.977
WP14	231.398	233.712	226.046	5.352	5.224
WP15	229.320	231.758	223.752	5.568	5.440

Notes: - CR: Carbon Steel exposed at Reduit

CP: Carbon Steel exposed at Port Louis Bulk Sugar Terminal

WR: Weathering Steel exposed at Reduit

WP: Weathering Steel exposed at Port Louis Bulk Sugar Terminal

3.1.6.3. Reduction in Thickness of Exposed Samples

Using the mass loss of the exposed samples, the thickness reduction was calculated (Q.C. Zhang et al., 2003):

$$d = \frac{m}{A \times \rho} \quad (5)$$

Where d is the thickness reduction (mm)
m is the mass loss (g)
A is the surface area of the specimen (mm^2)
ρ is the density (g/mm^3)

Tables 9 and 10 contain the area and density of carbon steel and weathering steel exposed at Reduit respectively.

Table 9: Area and density of carbon steel (Reduit)

Specimen	Length (mm)	Width (mm)	Thickness (mm)	Mass Before Exposure (g)	Density (g/mm^3)	Area (mm^2)
CR1	150.07	98.56	1.47	171.269	7.877E-03	1.479E+04
CR2	150.28	98.36	1.44	168.840	7.932E-03	1.478E+04
CR3	150.09	98.36	1.46	171.177	7.942E-03	1.476E+04
CR4	150.31	98.42	1.49	171.789	7.794E-03	1.479E+04
CR5	150.16	98.51	1.42	171.378	8.159E-03	1.479E+04
CR6	149.5	99.59	1.42	171.846	8.128E-03	1.489E+04
CR7	149.53	99.63	1.42	172.228	8.141E-03	1.490E+04
CR8	149.52	99.64	1.44	170.095	7.929E-03	1.490E+04
CR9	149.58	99.59	1.45	171.490	7.939E-03	1.490E+04
CR10	149.66	98.31	1.41	169.172	8.155E-03	1.471E+04
CR11	149.98	98.46	1.45	171.410	8.005E-03	1.477E+04
CR12	149.37	99.22	1.42	168.734	8.018E-03	1.482E+04
CR13	149.49	99.55	1.43	169.970	7.987E-03	1.488E+04
CR14	150.07	98.38	1.48	171.170	7.834E-03	1.476E+04
CR15	149.51	99.68	1.42	171.913	8.123E-03	1.490E+04
CR16	148.06	96.43	1.42	172.647	8.516E-03	1.428E+04
CR17	149.89	98.36	1.49	171.547	7.809E-03	1.474E+04
CR18	150.12	98.30	1.45	171.117	7.997E-03	1.476E+04

Table 10: Area and density of weathering steel (Reduit)

Specimen	Length (mm)	Width (mm)	Thickness (mm)	Mass Before Exposure (g)	Density (g/mm^3)	Area (mm^2)
WR1	151.14	100.3	1.84	230.182	8.252E-03	1.516E+04
WR2	151.15	100.23	1.89	230.574	8.053E-03	1.515E+04
WR3	150.04	100.36	1.87	227.228	8.070E-03	1.506E+04
WR4	151.02	99.98	1.88	229.296	8.078E-03	1.510E+04
WR5	150.44	100.10	1.91	226.933	7.890E-03	1.506E+04
WR6	151.42	100.19	1.88	230.986	8.099E-03	1.517E+04
WR7	151.28	100.28	1.90	231.298	8.025E-03	1.517E+04
WR8	151.42	100.18	1.88	230.247	8.074E-03	1.517E+04
WR9	151.38	100.14	1.88	229.758	8.062E-03	1.516E+04
WR10	151.36	100.28	1.95	232.183	7.845E-03	1.518E+04
WR11	151.26	100.29	1.96	230.993	7.769E-03	1.517E+04
WR12	149.84	100.28	1.90	228.014	7.987E-03	1.503E+04
WR13	149.87	100.29	1.88	228.614	8.090E-03	1.503E+04
WR14	149.98	100.36	1.85	227.092	8.155E-03	1.505E+04
WR15	151.45	100.20	1.96	232.241	7.808E-03	1.518E+04
WR16	149.94	100.38	1.90	227.313	7.949E-03	1.505E+04
WR17	151.15	100.28	1.90	230.743	8.012E-03	1.516E+04
WR18	151.40	100.31	1.90	231.720	8.030E-03	1.519E+04
WR19	151.00	100.04	1.88	229.820	8.092E-03	1.511E+04
WR20	151.65	100.28	1.92	229.733	7.868E-03	1.521E+04

Tables 11 and 12 contain the area and density of carbon steel and weathering steel exposed at Port Louis at the Sugar Bulk Terminal respectively.

Table 11: Area and density of carbon steel (Port Louis)

	Carbon Steel (Port Louis)					
Specimen	Length (mm)	Width (mm)	Thickness (mm)	Mass Before Exposure (g)	Density (g/mm^3)	Area (mm^2)
CP1	149.62	99.68	1.44	172.636	8.038E-03	1.491E+04
CP2	149.95	98.39	1.37	166.091	8.217E-03	1.475E+04
CP3	150.16	98.32	1.42	170.746	8.145E-03	1.476E+04
CP4	150.21	98.39	1.49	171.406	7.784E-03	1.478E+04
CP5	150.25	98.41	1.42	171.221	8.155E-03	1.479E+04
CP6	150.21	98.40	1.40	171.426	8.284E-03	1.478E+04
CP7	150.17	98.36	1.41	171.704	8.244E-03	1.477E+04
CP8	149.51	99.62	1.43	172.872	8.117E-03	1.489E+04
CP9	150.28	98.38	1.44	171.062	8.035E-03	1.478E+04
CP10	150.17	98.48	1.46	171.74	7.954E-03	1.479E+04
CP11	150.25	98.37	1.44	170.666	8.019E-03	1.478E+04
CP12	150.19	98.41	1.42	170.835	8.140E-03	1.478E+04
CP13	149.78	99.62	1.46	174.113	7.992E-03	1.492E+04
CP14	149.64	98.38	1.42	170.504	8.156E-03	1.472E+04
CP15	150.20	98.40	1.44	171.118	8.040E-03	1.478E+04
CP16	149.73	98.42	1.42	170.648	8.155E-03	1.474E+04
CP17	150.12	98.44	1.43	171.614	8.121E-03	1.478E+04
CP18	150.10	98.44	1.44	171.096	8.041E-03	1.478E+04
CP19	150.10	98.38	1.42	165.571	7.896E-03	1.477E+04
CP20	149.98	98.42	1.42	169.939	8.108E-03	1.476E+04

Table 12: Area and density of weathering steel (Port Louis)

			Weathering Steel (Port Louis)			
Specimen	Length (mm)	Width (mm)	Thickness (mm)	Mass Before Exposure (g)	Density (g/mm³)	Area (mm²)
WP1	150.24	100.32	1.92	229.338	7.925E-03	1.507E+04
WP2	150.24	100.30	1.89	228.799	8.034E-03	1.507E+04
WP3	150.08	100.31	1.94	230.282	7.885E-03	1.505E+04
WP4	150.32	100.32	1.89	229.035	8.036E-03	1.508E+04
WP5	150.19	100.22	1.91	231.614	8.056E-03	1.505E+04
WP6	150.21	100.34	1.90	231.39	8.080E-03	1.507E+04
WP7	151.34	100.14	1.90	229.306	7.963E-03	1.516E+04
WP8	150.16	100.33	1.92	229.857	7.946E-03	1.507E+04
WP9	150.03	100.00	1.93	230.376	7.956E-03	1.500E+04
WP10	151.19	99.74	1.89	228.842	8.029E-03	1.508E+04
WP11	150.11	100.29	1.90	230.166	8.047E-03	1.505E+04
WP12	150.02	100.08	1.92	230.217	7.986E-03	1.501E+04
WP13	149.90	100.22	1.92	228.184	7.911E-03	1.502E+04
WP14	151.28	100.19	1.91	231.398	7.993E-03	1.516E+04
WP15	150.27	100.32	1.93	229.32	7.882E-03	1.508E+04
WP16	150.01	100.11	1.93	230.008	7.936E-03	1.502E+04
WP17	149.81	100.24	1.91	228.586	7.970E-03	1.502E+04
WP18	149.82	100.22	1.90	227.638	7.979E-03	1.501E+04
WP19	150.08	100.18	1.91	230.582	8.029E-03	1.504E+04
WP20	150.11	100.25	1.90	230.04	8.046E-03	1.505E+04
WP21	150.16	100.32	1.88	231.731	8.182E-03	1.506E+04
WP22	150.16	100.17	1.89	230.599	8.112E-03	1.504E+04
WP23	151.00	99.73	1.86	228.597	8.161E-03	1.506E+04
WP24	151.09	101.18	1.89	234.379	8.112E-03	1.529E+04

The area, A and density, ρ of the samples were calculated as follows

$$A = L \times W \quad (6)$$

$$\rho = \frac{M_{be}}{L \times W \times t} \quad (7)$$

Where L is the length

W is the width

t is the thickness of the samples before exposure

The dimension loss of weathering and carbon steels exposed at Réduit and Port Louis are tabulated in Tables below.

Table 13: Thickness loss of carbon and weathering steels in Reduit

	Specimen	Corrected Mass loss (g)	Area (mm²)	Density (g/mm³)	Thickness loss (mm)
Carbon Steel					
1st Batch (3 months)	CR1	2.179	1.479E+04	7.877E-03	0.0187
	CR2	1.979	1.478E+04	7.932E-03	0.0169
	CR3	2.125	1.476E+04	7.942E-03	0.0181
2nd Batch (6 months)	CR5	3.990	1.479E+04	8.159E-03	0.0331
	CR6	4.029	1.489E+04	8.128E-03	0.0333
	CR7	4.237	1.490E+04	8.141E-03	0.0349
3rd Batch (10 months)	CR9	6.110	1.490E+04	7.939E-03	0.0517
	CR10	5.642	1.471E+04	8.155E-03	0.0470
	CR11	5.933	1.477E+04	8.005E-03	0.0502
4th Batch (13 months)	CR13	6.614	1.488E+04	7.987E-03	0.0556
	CR14	6.628	1.476E+04	7.834E-03	0.0573
	CR15	6.471	1.490E+04	8.123E-03	0.0534
Weathering Steel					
1st Batch (3 months)	WR1	2.593	1.516E+04	8.252E-03	0.0207
	WR2	2.175	1.515E+04	8.053E-03	0.0178
	WR3	2.416	1.506E+04	8.070E-03	0.0199
2nd Batch (6 months)	WR5	2.762	1.506E+04	7.890E-03	0.0232
	WR6	3.368	1.517E+04	8.099E-03	0.0274
	WR7	3.245	1.517E+04	8.025E-03	0.0267
3rd Batch (10 months)	WR9	3.905	1.516E+04	8.062E-03	0.0320
	WR10	4.231	1.518E+04	7.845E-03	0.0355
	WR11	4.103	1.517E+04	7.769E-03	0.0348
4th Batch (13 months)	WR13	4.667	1.503E+04	8.090E-03	0.0384
	WR14	4.290	1.505E+04	8.155E-03	0.0349
	WR15	4.379	1.518E+04	7.808E-03	0.0370

Table 14: Thickness loss of carbon and weathering steels in Port Louis

	Specimen	Corrected Mass loss (g)	Area (mm²)	Density (g/mm³)	Thickness loss (mm)
Carbon Steel					
1st Batch (3 months)	CP1	2.038	1.491E+04	8.038E-03	0.0170
	CP2	2.032	1.475E+04	8.217E-03	0.0168
	CP3	2.177	1.476E+04	8.145E-03	0.0181
2nd Batch (6 months)	CP5	3.894	1.479E+04	8.155E-03	0.0323
	CP6	5.121	1.478E+04	8.284E-03	0.0418
	CP7	4.660	1.477E+04	8.244E-03	0.0383
3rd Batch (10 months)	CP9	6.801	1.478E+04	8.035E-03	0.0572
	CP10	6.502	1.479E+04	7.954E-03	0.0553
	CP11	6.241	1.478E+04	8.019E-03	0.0527
4th Batch (13 months)	CP13	7.572	1.492E+04	7.992E-03	0.0635
	CP14	7.403	1.472E+04	8.156E-03	0.0617
	CP15	7.869	1.478E+04	8.040E-03	0.0662
Weathering Steel					
1st Batch (3 months)	WP1	1.604	1.507E+04	7.925E-03	0.0134
	WP2	2.033	1.507E+04	8.034E-03	0.0168
	WP3	1.992	1.505E+04	7.885E-03	0.0168
2nd Batch (6 months)	WP5	3.313	1.505E+04	8.056E-03	0.0273
	WP6	4.223	1.507E+04	8.080E-03	0.0347
	WP7	4.061	1.516E+04	7.963E-03	0.0336
3rd Batch (10 months)	WP9	4.464	1.500E+04	7.956E-03	0.0374
	WP10	4.716	1.508E+04	8.029E-03	0.0389
	WP11	4.394	1.505E+04	8.047E-03	0.0363
4th Batch (13 months)	WP13	4.977	1.502E+04	7.911E-03	0.0419
	WP14	5.224	1.516E+04	7.993E-03	0.0431
	WP15	5.440	1.508E+04	7.882E-03	0.0458

3.2. Monitoring Of Atmospheric Parameters

To monitor the atmospheric parameters at both sites, the wet candle method and the lead dioxide sulfation cylinder, according to ISO 9225 (2012), were used to obtain the chloride (airborne salinity) and sulphur dioxide deposition rate respectively.

3.2.1.   Wet Candle method

The wet candle method consists of a wet fabric which acted an absorbent for chloride particulates or droplets. The free ends of the fabric were needed to be immersed in a solution in order for it to be kept wet. The solution was then analysed for the determination of the rate of chloride deposition.

Nylon rod of diameter 30mm were turned to 25 mm and cut at a length of 20 cm to be used as a central rod over which a double layer of surgical gauze were wounded to the form the wick.

The wick was inserted through a stopper with 12 cm to be exposed. The assembly was then inserted in 500 mL glass bottle containing 200 mL of glycerol solution.
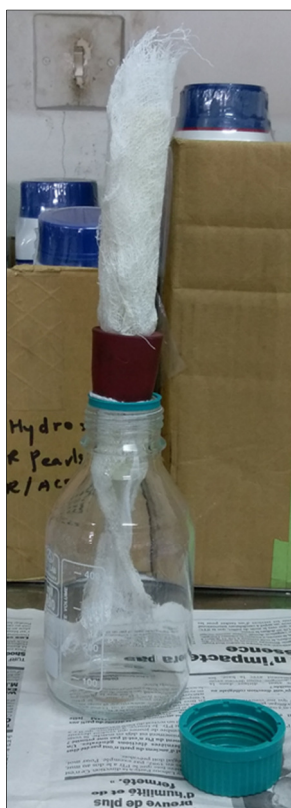
Figure 17: The wet candle test

A solution of glycerol was prepared by mixing 1 part of pure glycerol and 4 parts of distilled water, to which 20 drops of octanoic acid ($C_8H_{16}O_2$) were added to prevent the growth of fungi such as *Aspergillus niger*.

Figure 18: Glycerol solution with octanoic acid

To collect the glycerol solution, after being exposed for 30 ± 2 days, the stopper was loosened and both ends of the wick was washed with 200 mL distilled water, with the water being collected in the bottle. Analysis of chloride ions was performed using the glycerol solution.

Figure 19: The exposed wet candle

3.2.2. Lead Dioxide Sulfation Cylinders

For this experimentation, the lead dioxide reacted with the atmospheric sulphur dioxide to form lead sulphate. The analysis of the lead sulphate helped to determine the rate of deposition of sulphur dioxide.

PVC tube of diameter 40mm were cut at a length of 15 cm. Cloth of yarn count 60 of dimensions (13 x 12) cm were cut and tapped to the tube, leaving a cloth area of width 12.6 cm and length 10 cm (as shown in figure 20) on which the lead dioxide paste was applied.

Figure 20: Cloth tapped on PVC tube

Prior to preparing the paste, the tragacanth gum solution was prepared, as shown in figure 21, by dissolving 2g of tragacanth gum powder in 10 mL of ethanol followed by 190 mL of distilled water.

Figure 21: Tragacanth Gum Solution

Using a syringe, 5 mL of the tragacanth gum solution was measured and was mixed in 5g of lead dioxide.
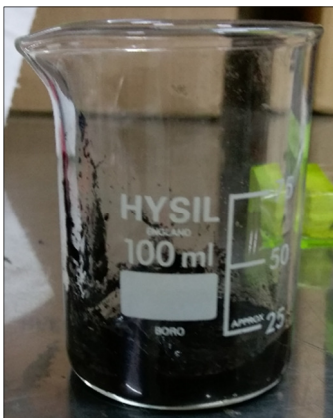
Figure 22: Lead dioxide paste

The paste was applied using a clean rubber glove for surgical use and the cylinder, as shown in figure 23, was left to dry in a desiccator.

Figure 23: Lead dioxide cylinder

After 30 ± 2 days of exposure, the lead dioxide cylinder was removed from the test site and stored in the desiccator.

For analysis, cloth was removed from the PVC cylinder and was placed in 500 mL beaker containing with 100 mL distilled water. 5g of sodium carbonate was added and the content is

mixed until dissolved.

The mixture was boiled for 30 min, keeping the volume of water at 100 mL. Once cooled, the solution was filtered and rinsed using a filter paper, following which sulphate analysis was performed.

Figure 24: Boiling of lead dioxide solution

3.2.3. Exposure period

Atmospheric conditions were monitored at both locations, Reduit and Port-Louis (Bulk Sugar Terminal). Table 15 contains the set-up and collection date and time of atmospheric monitoring set-up.

Table 15: First Batch Exposure Time

BATCH 1

SET	Date (M/D/Y) and Time	
	Set up	*Collection*
R1	6/29/17 10:30 AM	8/1/17 10:00 AM
P1	7/20/17 10:30 AM	8/25/17 10:00 AM

R1 and P1 refers to the sulphation cylinders at Reduit and Port Louis respectively.

Figure 25: Monitoring apparatus exposed at Reduit

3.2.4. Chloride and Sulphate Analysis

To test for chloride ions, silver nitrate titration was performed. On the other hand, to determine the amount of sulphur dioxide, sulphate analysis was conducted using gravimetric methods by barium sulphate precipitation.

3.2.4.1. Silver Nitrate Titration

According to ASTM D4458, sliver nitrate solution and potassium chromate solution were prepared as follows.

- 2mg Cl⁻/mL Silver Nitrate Solution

Table 16: Preparation of silver nitrate solution

Chemical reagents	Quantity
Silver Nitrate	9.5834g
Distilled Water	700 mL
Concentrated Nitric Acid	1 drop
Dilute solution to 1L with distilled water	

- 5% Potassium Chromate Solution (indicator)

Table 17: Preparation of potassium chromate

Chemical reagents	Quantity
Potassium Chromate	5g
Distilled Water	100 mL

Since the indicator needs to be neutral, solution of 1 part nitric acid and 19 parts distilled water was prepared to adjust the pH from 9.98 to 7.04.

The glycerol solution was filtered to remove any suspended particles. 100 mL of the solution was transferred to a conical flask, as shown in figure 26. The pH was measured and should be between 6.5 and 8, if not 1g of sodium bicarbonate was added and stirred to dissolve.

1 mL of 5% chromate indicator was added.

Figure 26: Glycerol solution before titration

Solution is titrated with silver nitrate solution to a permanent orange colour (end point) preceding the brick red coloured precipitate as in figure below.

Figure 27: Endpoint of titration

The volume of silver nitrate used was calculated as follows.

$$Volume\ of\ Silver\ Nitrate\ Used = V_f - V_i \qquad (8)$$

Where V_f is the final volume of silver nitrate (mL)
V_i is the initial volume of silver nitrate (mL)

The correct volume of silver nitrate used was obtained by performing the following calculation.

$$Corrected\ Volume\ of\ silver\ nitrate\ used = V_{av} - V_{ac} \qquad (9)$$

Where V_{av} is the average volume of silver nitrate used (mL)
V_{ac} is the average volume of silver nitrate used for the control sample (mL)

Table 18: Volume of silver nitrate

Set	Test	Initial Volume Silver Nitrate (mL)	Final Volume Silver Nitrate (mL)	Volume Silver Nitrate Used (mL)	Average Volume Silver Nitrate Used (mL)	Corrected Volume/mL
Control	Test 1	10.8	11.7	0.9	0.933	-
	Test 2	12.3	13.3	1.0		
	Test 3	14.2	15.1	0.9		
R1	Test 1	2.9	5.0	2.1	1.933	1.00
	Test 2	6.6	8.5	1.9		
	Test 3	8.8	10.6	1.8		
P1	Test 1	5.3	8.7	3.4	3.367	2.43
	Test 2	9.0	12.3	3.3		
	Test 3	13.0	16.4	3.4		

41

3.2.4.2. *Barium Sulphate Gravimetric Analysis*

The specifications of the solutions were obtained from ASTM D2010.

- 50g/L Barium Chloride Solution

Table 19: Preparation of Barium Chloride

Chemical reagents	Quantity
Barium Chloride	50g
Dissolve and dilute to 1L with distilled water	

- 0.05 N HCl Solution

Table 20: Specifications of Hydrochloric Acid

Specifications of Hydrochloric Acid	
Weight Percentage (% w/w)	35.4
Density (g/mL)	1.18
Formula Weight (g/mol)	36.46

The molarity of the acid was calculated as follows.

$$Molarity\ (M) = \frac{Weight\ Percentage\ \times Density}{Formula\ Weight} \times 10 \quad (10)$$

The molarity of 11.457 M was obtained.

Since 1 mole of hydrochloric acid contains 1 mole of H^+, then 1M of HCl has a normality of 1N. Consequently, the hydrochloric has the same normality as its molarity.

To obtain 0.05 N hydrochloric acid, the stock concentrate of 11.457 N had to be diluted.

The dilution of the solution was calculated as follows.

$$N_1 v_1 = N_2 v_2 \quad (11)$$

Where N_1 and v_1 are the normality and volume of the stock concentrate
N_2 and v_2 are the normality and volume of the dilute solution.

To prepare 500 mL of 0.05M of HCl, 2.182 mL of the stock solution was diluted and adjusted to the final required volume.

Sets of filter paper and crucible were weighed. 25 mL of the sample solution was transferred in a beaker. 10 mL of 0.05 M HCl was added and the solution was heated.

25 mL of barium chloride was poured gradually in the solution in three parts and the solution was stirred and left to stand. Drops of barium chloride were added and if no more precipitate is formed, as shown in figure 28, the solution is filtered. Otherwise, excess of barium chloride was added until no precipitation occurred.
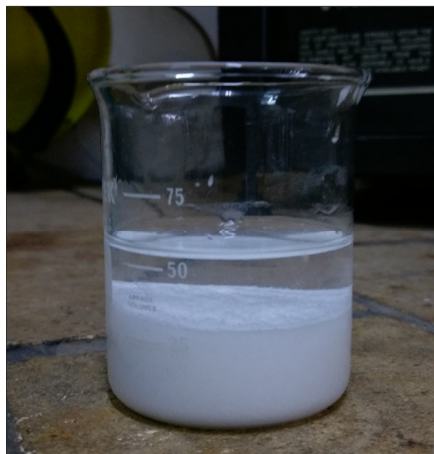
Figure 28: Precipitation of barium sulphate

Once filtrated, the filter paper with the precipitate was placed in the crucible and was dried at $115^{o}C$ for 1 hour.

Figure 29: Dried barium sulphate

The mass of the precipitate was calculated as follows.

$$Mass\ of\ precipitate\ (barium\ sulphate) = M_{fp+C+p} - M_{fp+C} \qquad (12)$$

Where M_{fp+c+p} is the combined mass of filter paper, crucible and the precipitate (g)
M_{fp+c} is the combined mass of filter paper and crucible (g)

The corrected mass of the precipitate was found as such;

$$Corrected\ Mass\ of\ precipitate = M_{av} - M_{ac} \qquad (13)$$

Where M_{av} is the average mass of the precipitate (g)
M_{ac} is the average control mass of the precipitate (g)

Table 21: Mass of precipitate (barium sulphate)

Set	Test	Mass (g) (Filter paper + Crucible)	Mass (g) (Filter paper + Crucible + precipitate)	Mass (g) (precipitate)	Average Mass (g) (precipitate)	Corrected Mass (g) (precipitate)
	Test 1	66.441	68.366	1.925		
Control	Test 2	61.688	63.686	1.998	2.0307	-
	Test 3	61.991	64.160	2.169		
	Test 1	66.421	68.543	2.122		
R1	Test 2	61.630	63.656	2.026	2.0920	0.061
	Test 3	61.998	64.126	2.128		
	Test 1	66.451	68.506	2.055		
P1	Test 2	61.710	63.747	2.037	2.0453	0.015
	Test 3	62.056	64.100	2.044		

3.2.5.   Deposition Rate of Chloride and Sulphur Dioxide

3.2.5.1.   Chloride (airborne salinity) Rate Deposition

Table 22 below contains the area of the gauze and titre value of the silver nitrate.

Table 22: Titre and gauze area

Length (L) (m)	0.12
Diameter (D) (m)	0.025
Area (A) (m^2)	9.42E-03
Titre (T) (mg Cl⁻/mL)	2.00

The area of the gauze was calculated as follows.

$$A = \pi D L \qquad (14)$$

Where L is the length of the wick exposed

D is the diameter of the nylon rod.

Table 23: Rate of chloride deposition

Set	Sample Volume (mL)	Corrected Volume Silver Nitrate (mL)	Days Exposed	Rate (mg Cl⁻/ L)	Rate (mg Cl⁻/m²/ days)	Rate (g Cl⁻/m²/ yr.)
R1	100	1.00	32.98	20.00	32.17	11.74
P1	100	2.43	35.98	48.67	71.76	26.19

The rate of chloride deposition was calculated as follows.

$$mg\ Cl^-/L = \frac{(ml\ silver\ nitrate)\ \times T\ \times 1000}{ml\ sample\ used\ for\ titration} \qquad (15)$$

Where T is titre (2 mg Cl⁻ /ml Silver Nitrate)

$$mg\ Cl^-/m^2/days = \frac{mg\ Cl^-/L}{2At} \qquad (16)$$

Where A is the exposed area of the gauze

t is the exposed time in days.

$$g\ Cl^-/m^2/yr = \frac{mg\ Cl^-/m^2/days}{1000} \times 365 \qquad (17)$$

The results are shown in Table 23.

3.2.5.2.   Sulphur Dioxide Rate Deposition

Table 24 below contains the area of the cloth, sample volume and aliquot.

Table 24: Cloth area and aliquot analysed

Length (m)	0.126
Width (m)	0.10
Area (m^2)	1.26E-02
Aliquot (mL)	25
Sample Volume (mL)	100

The area of the cloth was calculated as follows.

$$A = L \times W \quad (18)$$

Where L is the length of the cloth
W is the width of the cloth

Table 25: Rate of sulphur dioxide deposition

Set	Corrected Mass of precipitate in aliquot (g)	Days Exposed	Total Mass of SO$_2$ (mg)	Rate (mg SO$_2$ /m^2/ days)	Rate (g SO$_2$ /m^2/ yr.)
R1	0.061	32.98	67.344	162.50	59.31
P1	0.015	35.98	16.104	35.62	13.00

The rate of sulphur dioxide deposition was calculated as follows.

$$M = \frac{M_B \times 64.066 \times Total\ sample\ volume}{233.38 \times volume\ sample\ tested\ (aliquot)} \times 1000 \quad (18)$$

Where M is the mass of sulphur dioxide (mg)
M$_B$ is the mass of barium sulphate (g)

$$mg\ SO_2/mm^2/days = \frac{M}{A \times t} \quad (19)$$

Where A is the area of the cloth
t is the exposed time in days.

$$g\ SO_2/\ m^2/\ yr = \frac{mg\ SO_2/\ m^2/\ days}{1000} \times 365 \quad (20)$$

The results for the sulphation cylinders exposed at Reduit and Port Louis are given in Table 25.

3.2.6. Time of Wetness

Categorisation of the sites with respect to time of wetness was performed based on data available from previous studies.

3.3. Life Cycle Assessment of Carbon Steel

For this case study, a proper flow of the carbon steel was established where all stages of life of metal were thoroughly established, including recycled scraps. The quantitative input and output data were calculated in relation to this flow. The manufacturing of a product involves inflows of material and energy resources and outflows such as emissions to air, water and ground, waste and material for recycling. The product itself is also an outflow.

3.3.1. Goal and Scope

3.3.1.1. Goal

The goal of the study was to assess and compare the environmental impacts caused by different stages of the life cycle of carbon steel being used in Mauritius in a bid to determine the flow of the metal as well as the possibility of using a sustainable alternative.

3.3.1.2. Scope

A "cradle-to-gate" system boundary was considered for this life cycle assessment. It encompassed the production of steel using the Basic Oxygen Furnace, importation of steel and scrap from foreign countries, the distribution within Mauritius, transportation and production of steel rebars from scrap in Mauritius (Samlo) using the Electric Arc Furnace, transport and compaction of scrap for export purpose and exportation of scrap and steel from Mauritius.

Figure 30 illustrates the boundary system analysed for this study. The system was developed after surveying the use of carbon steel in Mauritius in the local industry.
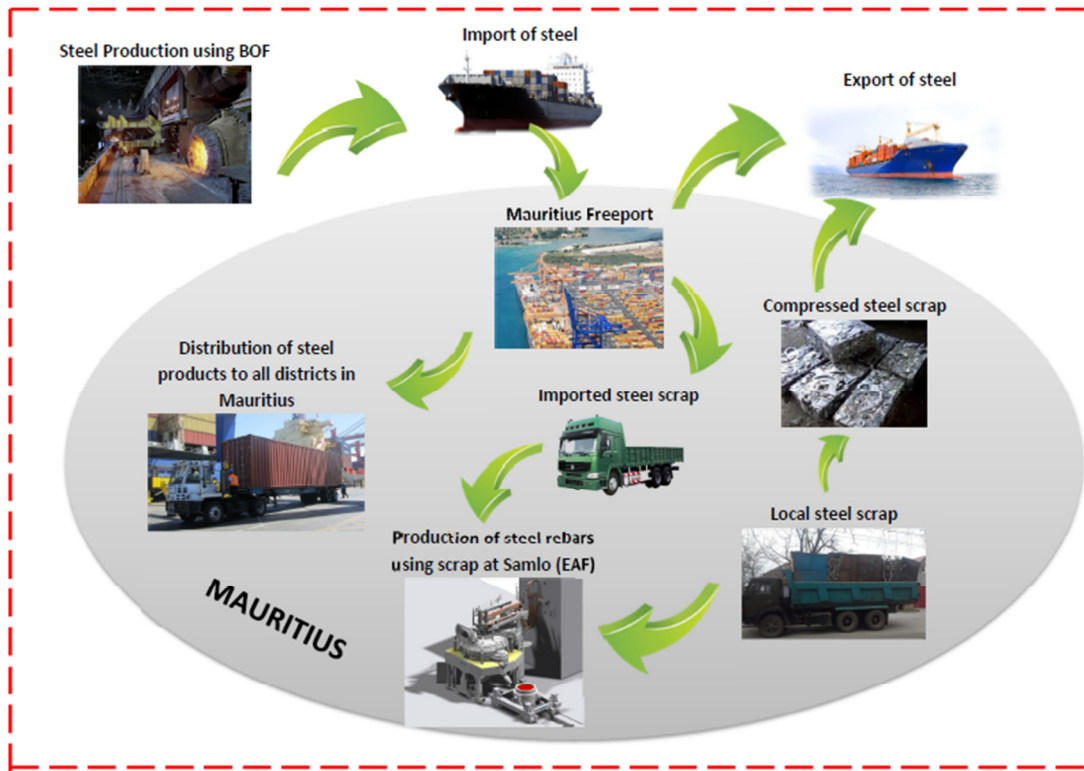
Figure 30: Boundary system of the LCA

Only amount of carbon steel imported for structural purposes such as sheets, plates, tubes, pipes, angle bars and other types of bars were taken into consideration, excluding high tensile steel rods used in the construction of concrete buildings, and other low-alloy or high alloy steels.

Data for the stages was collected from the various sources.

- For the production of steel through Basic Oxygen Furnace and recycling of scrap steel through Electric Arc Furnace- Burchart-Korol (2013)
- For the amount of steel imported and exported- the Central Statistics Office of Mauritius.
- For the overseas and inland transport of steel and scrap and compaction of scrap for exportation – ELCD (European Reference Life Cycle Database) v3.2

For the life cycles of the stages, the following assumption were made:-

- The shortest distance between the ports of two countries was considered.
- Equal amount of steel products was distributed to each district of Mauritius.
- Equal amount of scrap was collected and transported from each district to Samlo.
- Distance between approximately the centres of each district to destination (Shortest distance) was taken into consideration.
- Equal Amount of local scrap was processed in both metal briquetting companies.

48

3.3.1.3. *Functional Unit*

The following functional units were selected in order to have an overall insight on the impacts caused by the amount of steel used in Mauritius yearly:-

- The amount of steel/steel products (tonnes) being imported per year is used as the functional unit for the Basic Oxygen Furnace.

- The amount of scrap reaching Samlo (tonnes) per year is used as the functional unit for the Electric Arc Furnace.

3.3.2. *Life Cycle Inventory (LCI)*

Data were collected to build up the inventory for the life cycle assessment of carbon steel in Mauritius, as shown in figure 31. It quantified the inputs, energy and raw material requirements used, and the outputs, products, by-products and environmental emissions.
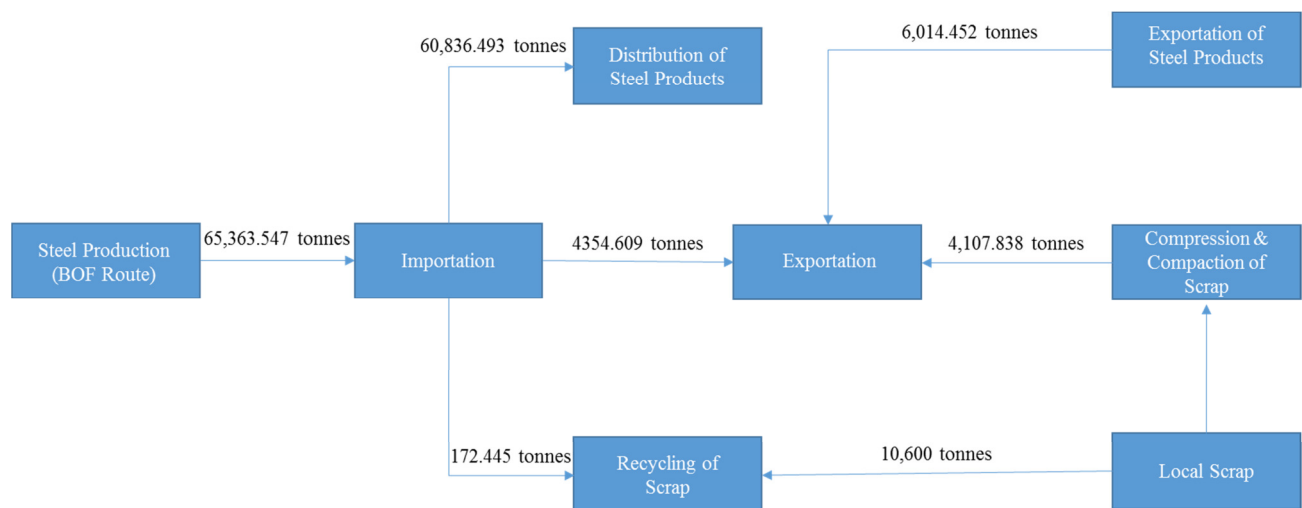
Figure 31: Flow of Steel in Mauritius

Table 26 summarizes data on the import and export of steel has been collected from the Central Statistics Office.

Table 26: Import and Export of Steel

Item	Quantity Imported / kg	Quantity Exported / kg	Quantity used in Mauritius / kg
Scrap	172,445	4,107,838	172,445
Pig iron	29,657	-	29,657
Semi-products	6,951,598	-	6,951,598
Flat product (coiled)	923,580	48,554	923,580
Flat product (not in coil)	2,789,767	113,519	2,789,767
Other flat rolled products	13,839,932	96,696	13,756,528
Bars/Rods	6,728,523	164,775	6,577,118
U/i/h/L/t sections (Galvanised)	413,022	188	412,834
U/i/h/L/t sections (Not galvanised)	2,415,862	2,722	2,413,140
Angle/shape (Galvanised)	550,413	70,441	479,972
Angle/shape (Not Galvanised)	938,163	427	937,736
Angle/shape (Other)	3,737	0	3,737
Wire	1,330,204	0	1,330,204
Sheet piling	1,205,122	94,802	1,110,320
Railway products	201,659	741	200,918
Tubes/pipes (Other)	3,190,312	18,693	3,171,619
Tubes/pipes (Galvanised)	560,860	676,857	-
Tubes/pipes (Not galvanised)	1,544,468	4,927,706	-
Tube/pipe fittings	659,847	2,892	656,955
Bridge/tower sections	361,345	1,958	359,387
Door/window	179,184	23,914	155,270
Structures	5,991,459	164,948	5,826,511
Tank/can/container/drum	3,059,210	1,165,105	1,894,105
Wire/cable/band	662,879	2,418,586	574,503
Cloth/grill/fencing/expanded metal	409,889	8136	401,753
Chains	164,114	6491	158,138
Anchors/grapnels	47,089	140	46,949
Nail/screw/nut/bolt/pin/needle	2,596,520	106,118	2,486,159
Springs	727,426	200	727,226
Cooking appliances	4,183,070	172,800	4,010,270
Radiators/air heaters	13,769	773	12,996
Gloves/scouring pads	96,314	1,957	94,357
Kitchen utensils	509,668	23699	485,969
Sinks/baths/sanitary wares	206,905	1,344	205,561

Grinding balls/forged/stamped articles	842,331	6980	835,351
Other articles	863,204	46,899	816,305
TOTAL	**65,363,547**	**14,476,899**	**61,008,938**

It was found that a total of 65,363,547 kg of steels were imported in Mauritius and 14,476,899 kg were exported yearly.

3.3.2.1. *Life Cycle Inventory for Steel production (BOF route)*

Since there is no steel production using the Basic Oxygen Furnace in Mauritius, data was unavailable. To model the process, input and output data obtained from research paper (Burchart-Korol, 2013) were used. Under the BOF route, six processes; the iron ore sinter plant, blast furnace, lime production plant, basic oxygen furnace, continuous casting plant and hot rolling plant, were analysed. Their inputs and outputs for 1 ton of steel were extracted and were adjusted for 1 tonne. Tables 27 and 28 contain the adjusted inputs and outputs for steel production respectively. The total amount of steel imported of 65363.547 tonnes was the functional unit for the steel production.

Table 27: Inputs for Production of Steel

Inputs	Unit	Iron Ore Sinter Plant	Blast Furnace	Lime Production Plant	Basic Oxygen Furnace	Continuous Casting Plant	Hot Rolling
Material							
Iron ores	kg/tonne	1326.00	40.53	0.00	0.00	0.00	0.00
Limestone	kg/tonne	198.63	0.00	135.76	0.00	0.00	0.00
Dolomite	kg/tonne	37.76	0.00	0.00	5.89	0.00	0.00
Quicklime	kg/tonne	22.72	0.00	0.00	68.86	0.00	0.00
Iron ore sinter	kg/tonne	0.00	1441.80	0.00	0.00	0.00	0.00
Pellets	kg/tonne	0.00	275.63	0.00	0.00	0.00	0.00
Pig iron	kg/tonne	0.00	0.00	0.00	1044.28	0.00	0.00
Iron scrap	kg/tonne	0.00	0.00	0.00	325.84	0.00	0.00
Crude steel	kg/tonne	0.00	0.00	0.00	0.00	1149.57	0.00
Cast Steel	kg/tonne	0.00	0.00	0.00	0.00	0.00	395.04
Lubricating oil	kg/tonne	3.86	2.41	0.03	0.00	2.71	37.32
Refractory	kg/tonne	0.00	0.00	0.00	69.67	0.15	0.00
Tap water	m^3/tonne	0.00	0.39	0.00	99.89	0.60	14.63

	Unit						
Circulating cooling water	m³/tonne	0.47	25.45	0.00	0.00	10.78	1.54
Sludges	kg/tonne	23.76	0.00	0.00	0.00	0.00	0.00
Dust	kg/tonne	54.82	0.00	0.00	0.00	0.00	0.00
Scale	kg/tonne	14.43	0.00	0.00	0.00	0.00	0.00
Energy							
Electricity	kWh/tonne	87.32	28.14	2.78	30.65	11.71	44.64
Anthracite	kg/tonne	11.64	11.78	0.00	0.00	0.00	0.00
Coke breeze	kg/tonne	65.96	0.00	0.00	0.00	0.00	0.00
Coke	kg/tonne	0.00	472.18	0.00	0.00	0.00	0.00
Coke oven gas	m³/tonne	5.30	80.22	0.60	4.24	0.00	42.73
BF gas	m³/tonne	7.99	657.18	1.32	9.32	0.00	31.59
BOF gas	m³/tonne	0.40	0.00	0.00	0.00	0.00	0.00
Natural gas	m³/tonne	0.00	0.43	6.10	0.45	0.11	2.99

Table 28: Outputs for Production of Steels

Outputs	Unit	Iron Ore Sinter Plant	Blast Furnace	Lime Production Plant	Basic Oxygen Furnace	Continuous Casting Plant	Hot Rolling
Products							
Iron Ore Sinter	kg/tonne	1441.8	0	0	0	0	0
Pig Iron	kg/tonne	0	1044.2778	0	0	0	0
Quicklime	kg/tonne	0	0	91.58765	0	0	0
Crude Steel	kg/tonne	0	0	0	1149.57	0	0
Cast Steel	kg/tonne	0	0	0	0	1102.5358	0
Rolled Steel	kg/tonne	0	0	0	0	0	395.0386
Co-Products							
BF Slag	kg/tonne	0	334.31092	0	0	0	0
BOF Slag	kg/tonne	0	0	0	155.579	0	0
Emissions							
CO_2	g/tonne	415727	891347.3	55750.83	32524.8	0	117740.9
SO_2	g/tonne	1117.97	11.025358	0	6.61521	0	4.410143
NO_2	g/tonne	852.26	11.025358	6.615215	4.41014	0	23.15325
CO	g/tonne	28499.4	1061.742	5.512679	5288.86	0	20.94818

Heavy Metals	g/tonne	150.529	69.029768	0.606395	83.5391	0	0.055127
Pb	g/tonne	6.73649	0.0551268	0.033076	1.06946	0	0
Cr	g/tonne	0.0441	0.0220507	0	0.14333	0	0
Cd	g/tonne	0.1323	0	0	0.05513	0	0
Cu	g/tonne	0.7387	0.5402426	0.033076	3.55017	0	0
Zn	g/tonne	1.19074	0.9922822	0.088203	8.62183	0	0
Ni	g/tonne	0.06615	0.0771775	0	0.31974	0	0
Fe	g/tonne	141.621	67.342889	0.429989	69.7795	0	0.055127
Dust	g/tonne	505.568	96.923925	17.67365	208.346	0	0.099228
HF	g/tonne	0.57332	0	0	0	0	0
HCl	g/tonne	5.50165	0	0	0	0	0
H$_2$S	g/tonne	0	0.1212789	0	0	0	0
HCN	g/tonne	0	0.9702315	0	0	0	0

Waste

Wastewater Refractory	m^3/tonne	0.42999	0.2205072	0.429989	1.23484	0.8269019	1.565601
Waste	kg/tonne	0	0.6284454	0	6.36163	2.1168688	0

Recycled Materials

BF gas	m^3/tonne	0	707.39802	0	0	0	0
BOF gas	m^3/tonne	0	0	0	0.39691	0	0
Sludges	kg/tonne	1.97354	0.9922822	0	20.7938	0	0
Dust	kg/tonne	36.1521	14.421169	2.425579	1.81918	0	0
Iron Scrap	kg/tonne	0	11.984564	0	21.1577	28.390298	33.53914
Scale	kg/tonne	0	0	0	0	2.5799338	11.86329

3.3.2.2. *Life Cycle Inventory for import and export of steel products*

Data obtained from Central Statistics Office has been used to determine the amount of steel that is imported and exported from the different countries. The results are summarised in the table 29.

Note: 1 nautical mile = 1.852 km

Table 29: Distance and amount of steel imported and exported per country

Country	Distance (Nautical mile)	Distance (km)	Import (kg)	Export (kg)
Angola	4050	7501	-	1,557

Country				
Argentina	6040	11186	6	-
Australia	5805	10751	548,889	-
Austria	4650	8612	3,709	28
Bahamas	8794	16286	2,868	-
Bahrain	3194	5915	596	8
Bangladesh	3231	5984	20	170,000
Belgium	7002	12968	59,546	11
Botswana	1778	3293	274	1
Brazil	5619	10406	526	-
Bulgaria	4635	8584	36	-
Burundi	1930	3574	-	320,000
Cambodia	3368	6238	176	-
Cameroon	4660	8630	-	2
Canada	7976	14772	7,023	173
Chile	8471	15688	171	-
China	4948	9164	37,599,790	24,245
Comoros	918	1700	67	45,041
Congo	4094	7582	-	58,525
Cook Islands	7488	13868	5,000	10,230
Cote D'Ivoire	4962	9190	53	-
Croatia (Local name: Hrvatska)	4981	9225	60	-
Cyprus	3927	7273	98	-
Czech Republic	4788	8867	27,789	-
Denmark	7611	14096	6,985	437
Ecuador	9565	17714	2,541	-
Egypt	3576	6623	6,495	-
Fiji	6750	12501	241	-
Finland	8043	14896	2,130	-
France	5068	9386	993,384	1,230
Georgia	5095	9436	5	-
Germany	7204	13342	90,715	14,613
Greece	4095	7584	180	-
Hong Kong	4747	8791	252,067	-
Hungary	4536	8401	212	-
India	2178	4034	2,046,936	3,036,298
Indonesia	4262	7893	632,434	38,001

Iran (Islamic Republic of)	3399	6295	157	-
Ireland	6809	12610	379,282	-
Israel	3846	7123	520	-
Italy	4916	9104	732,599	-
Jamaica	8544	15823	-	140
Japan	5994	11101	537,835	-
Jordan	3576	6623	1	-
Kenya	1424	2637	185	-
Korea, Democratic	6102	11301	4,083	-
Korea, Republic of	5798	10738	176,024	9,107
Kuwait	3357	6217	1	-
Latvia	8017	14847	70	-
Luxembourg	4979	9221	1,064,178	-
Madagascar	815	1509	14,675	1,447,071
Malaysia	3586	6641	324,850	22,289
Maldives	1830	3389	257	9,978
Malta	4657	8625	23	-
Martinique	7657	14181	-	1
Mayotte	836	1548	463,631	593,813
Mexico	11198	20739	204	-
Morocco	6069	11240	189	-
Netherlands	7025	13010	705,342	20,112
New Zealand	6187	11458	13,339	17,269
Niger	3827	7088	20	-
Nigeria	4850	8982	7	320
Norway	7590	14057	174,036	-
Oman	2669	4943	4,715	-
Pakistan	2755	5102	21,668	1,117,038
Philippines	4489	8314	2,791	-
Poland	7814	14472	7,470	-
Portugal	6088	11275	45,425	547
Qatar	3142	5819	19	13,015
Reunion	132	244	79,713	382,444
Romania	4705	8714	35	-

Rwanda	1946	3604	-	3,969,602
Seychelles	946	1752	9,997	88,121
Singapore	3324	6156	416,468	131,263
Slovakia (Slovak Republic)	4626	8567	923	-
Slovenia	5013	9284	25	-
South Africa	2295	4250	6,494,373	363,101
Spain	6497	12032	1,720,563	14,379
Sri Lanka	2293	4247	933	-
Sweden	7676	14216	2,864	-
Switzerland	4850	8982	9,523	154
Taiwan	4916	9104	872,853	429
Tanzania, United Republic of	1354	2508	717	21
Thailand	4155	7695	1,301,196	-
Tunisia	4894	9064	205	-
Turkey	4494	8323	3,454,641	42
Uganda	1905	3528	-	52,405
Ukraine	5069	9388	29,913	-
United Arab Emirates	2956	5475	3,010,045	163,643
United Kingdom	7280	13483	710,271	1,374
United States	10299	19074	38,431	2,915
Vietnam	3970	7352	245,240	-
Zambia	1691	3132	-	5,696

From Ecoinvent Report No.14 (Spielmann et al., 2007), the following information in Table 30 was extracted and fuel consumption for importation and exportation were calculated and presented in Table 31.

Table 30: Ship and fuel specifications

Type of ship	**Transoceanic Freight ship**
Fuel	Heavy Fuel Oil
Specific fuel consumption (g/tkm)	2.5

Note: Distance in tkm = Distance in km *x* tonne of material transported.

Table 31: Distance and fuel consumption

Country	Import		Export	
	Freight Carriage (tkm)	Fuel consumption (kg)	Freight Carriage (tkm)	Fuel consumption (kg)
Angola	0	0	11679.057	29.198
Argentina	67.116	0.168	0	0
Australia	5901105.639	14752.764	0	0
Austria	31941.908	79.855	241.136	0.603
Bahamas	46708.248	116.771	0	0
Bahrain	3525.34	8.813	47.32	0.118
Bangladesh	119.68	0.299	1017280	2543.200
Belgium	772192.528	1930.481	142.648	0.357
Botswana	902.282	2.256	3.293	0.008
Brazil	5473.556	13.684	0	0
Bulgaria	309.024	0.773	0	0
Burundi	0	0	1143680	2859.200
Cambodia	1097.888	2.745	0	0
Cameroon	0	0.000	17.26	0.043
Canada	103743.756	259.359	2555.556	6.389
Chile	2682.648	6.707	0	0
China	344564475.6	861411.189	222181.18	555.453
Comoros	113.9	0.285	76569.7	191.424
Congo	0	0	443736.55	1109.341
Cook Islands	69340	173.350	141869.64	354.674
Cote D'Ivoire	487.07	1.218	0	0
Croatia (Local name: Hrvatska)	553.5	1.384	0	0
Cyprus	712.754	1.782	0	0
Czech Republic	246405.063	616.013	0	0
Denmark	98460.56	246.151	6159.952	15.400
Ecuador	45011.274	112.528	0	0
Egypt	43016.385	107.541	0	0
Fiji	3012.741	7.532	0	0
Finland	31728.48	79.321	0	0

France	9323902.224	23309.756	11544.78	28.862
Georgia	47.18	0.118	0	0
Germany	1210319.53	3025.799	194966.646	487.417
Greece	1365.12	3.413	0	0
Hong Kong	2215920.997	5539.802	0	0
Hungary	1781.012	4.453	0	0
India	8257339.824	20643.350	12248426.13	30621.065
Indonesia	4991801.562	12479.504	299941.893	749.855
Iran (Islamic Republic of)	988.315	2.471	0	0
Ireland	4782746.02	11956.865	0	0
Israel	3703.96	9.260	0	0
Italy	6669581.296	16673.953	0	0
Jamaica	0	0.000	2215.22	5.538
Japan	5970506.335	14926.266	0	0
Jordan	6.623	0.017	0	0
Kenya	487.845	1.220	0	0
Korea, Democratic	46141.983	115.355	0	0
Korea, Republic of	1890145.712	4725.364	97790.966	244.477
Kuwait	6.217	0.016	0	0
Latvia	1039.29	2.598	0	0
Luxembourg	9812785.338	24531.963	0	0
Madagascar	22144.575	55.361	2183630.139	5459.075
Malaysia	2157328.85	5393.322	148021.249	370.053
Maldives	870.973	2.177	33815.442	84.539
Malta	198.375	0.496	0	0
Martinique	0	0	14.181	0.035
Mayotte	717700.788	1794.252	919222.524	2298.056
Mexico	4230.756	10.577	0	0
Morocco	2124.36	5.311	0	0
Netherlands	9176499.42	22941.249	261657.12	654.143
New Zealand	152838.262	382.096	197868.202	494.671
Niger	141.76	0.354	0	0
Nigeria	62.874	0.157	2874.24	7.186
Norway	2446424.052	6116.060	0	0

Oman	23306.245	58.266	0	0
Pakistan	110550.136	276.375	5699127.876	14247.820
Philippines	23204.374	58.011	0	0
Poland	108105.84	270.265	0	0
Portugal	512166.875	1280.417	6167.425	15.419
Qatar	110.561	0.276	75734.285	189.336
Reunion	19449.972	48.625	93316.336	233.291
Romania	304.99	0.762	0	0
Rwanda	0	0	14306445.61	35766.114
Seychelles	17514.744	43.787	154387.992	385.970
Singapore	2563777.008	6409.443	808055.028	2020.138
Slovakia (Slovak Republic)	7907.341	19.768	0	0
Slovenia	232.1	0.580	0	0
South Africa	27601085.25	69002.713	1543179.25	3857.948
Spain	20701814.02	51754.535	173008.128	432.520
Sri Lanka	3962.451	9.906	0	0
Sweden	40714.624	101.787	0	0
Switzerland	85535.586	213.839	1383.228	3.458
Taiwan	7946453.712	19866.134	3905.616	9.764
Tanzania, United Republic of	1798.236	4.496	52.668	0.132
Thailand	10012703.22	25031.758	0	0
Tunisia	1858.12	4.645	0	0
Turkey	28752977.04	71882.443	349.566	0.874
Uganda	0	0.000	184884.84	462.212
Ukraine	280823.244	702.058	0	0
United Arab Emirates	16479996.38	41199.991	895945.425	2239.864
United Kingdom	9576583.893	23941.460	18525.642	46.314
United States	733032.894	1832.582	55600.71	139.002
Vietnam	1803004.48	4507.511	0	0
Zambia	0	0	17839.872	44.600
TOTAL	**549243341.7**	**1373108.354**	**43706061.52**	**109265.154**

For an importation of 549243341.7 tonne kilometre, the fuel consumption of 1373108.354 kg was required while 109265.154 kg of fuel was needed for an export freight carriage of 43706061.52 tkm.

3.3.2.3. *Life cycle inventory for recycling of steel (EAF route)*

Amount of steel scrap recycled at Samlo included the imported scrap and the local scrap steel collected. From Table 26, the amount of imported scrap was 172.445 tonnes while according to Mohee et al. (2009), the amount of local scrap metal handled per week was 200 tonnes, leading to an estimation of the 10,600 tonnes of local scrap handled yearly. Therefore 10,772.445 tonnes of scrap were recycled at Samlo. The inputs and outputs for 1 ton of carbon steel obtained by recycling were extracted (Burchart-Korol, 2013) and were adjusted for 1 tonne. Table 32 and 33 contain the adjusted inputs and outputs for recycling steel scrap through electric arc furnace. Since the functional unit being the amount of scrap reaching Samlo is also an input, the amount carbon steel obtained after recycling was calculated in order to quantify of the inputs consumed and output processed.

From Burchart-Korol (2013)

$$1 \; tonne \; of \; carbon \; steel \; requires \; 1324.377 \; kg \; of \; scrap$$

Amount of scrap processed was 10,772.445 tonnes which resulted in 8133.972 tonnes of carbon steel being manufactured.

Table 32: Inputs for Electric Arc Furnace

Inputs	Unit	Flux
Materials		
Scrap	tonnes	10,772.445
Quicklime	kg/tonne	49.28
Refractory	kg/tonne	65.53
Electrode	kg/tonne	2.44
Alloys	kg/tonne	2.46
Electricity	kWh/tonne	459.64
Natural gas	m^3/tonne	5.19

Table 33: Outputs for Electric Arc Furnace

Outputs	Unit	Flux
Products		
Crude steel	kg/tonne	1149.570011

	Co-Products	
EAF Slag	kg/tonne	211.8412348
	Emissions	
CO_2	g/tonne	296589.86
SO_2	g/tonne	7.72
NO_2	g/tonne	1.10
CO	g/tonne	2995.59
Heavy Metals	g/tonne	0.00
Pb	g/tonne	0.58
Cr	g/tonne	0.10
Cd	g/tonne	0.10
Cu	g/tonne	0.14
Zn	g/tonne	12.09
Ni	g/tonne	0.04
Dust	g/tonne	73.87
HF	g/tonne	0.04
	Waste	
Wastewater	m^3/tonne	0.54
Refractory waste	kg/tonne	7.43
	Recycled Materials	
Scrap	kg/tonne	8.19
Dust	kg/tonne	3.50
Sludge	kg/tonne	8.86

3.3.2.4. *Life cycle inventory for processing of scrap for export*

Two companies were found to compact and compress metal scraps into briquettes for exportation, namely (Mohee et al., 2009):

- **Runghen G. & Co**

In operation since 1967, ferrous, non-ferrous and e-scraps are collected from door-to-door, factories and workshop and are processed. The collected metals are sorted, graded and compressed into briquettes in order to be exported.

- **Steel Scrap Ltd**

Being located at Plaine Lauzun Port Louis and in operation since 1960, the company is involved in compacting ferrous, non-ferrous metals and also flakes PET bottles which are exported to countries like India, China and South Africa.

From Table 26, the amount of scrap processed and exported was found to be 4,107,838 kg with electricity being the energy input. This process was assumed not to provoke any emission with briquetted steel being the sole output.

3.3.2.5. *Life cycle inventory for transport in Mauritius*

For the life cycle inventory for transport in Mauritius, the distribution of imported steels to regions on the island and the conveyance of imported scrap as well as local scrap for recycling and for compaction for export purposes were analysed.

Life cycle inventory for transport for distribution of steel products

To build up this inventory, an assumption was made that equal amount of steel products was distributed to each district of Mauritius. From the data from the Central Statistics Office, the amount of imported products, excluding scrap was calculated.

Amount of steel to be transported = Total amount of steel used in Mauritius – Imported scrap
$$= 61,008,938 - 172,445$$
$$= 60,836,493 \text{ kg}$$
Amount of steel products transported to each district = 60,836,493 / 9 = 6,759,610 kg
$$= 6759.61 \text{ tonnes}$$
Table 34 contains the distance steels had to be transported to various regions in Midlands

Table 34: Transportation for the distribution of steel

Region	Distance (km)	Distance (tkm)
Freeport to Port Louis	1.94	13113.6434
Freeport to Flacq (Central Flacq)	37.90	256189.219
Freeport to Grand Port (New Grove)	40.59	274372.57
Freeport to Moka (Dagotière)	20.28	137084.891
Freeport to Pamplemousses	12.75	86185.0275
Freeport to Plaines Wilhems (Curepipe)	27.83	188119.946
Freeport to Rivière du Rempart (Poudre D'Or Hamlet)	21.67	146480.749
Freeport to Rivière Noire (Bambous)	18.30	123700.863

Freeport to Savanne (Chamouny)	44.90	303506.489
TOTAL		**1528753.4**

The transportation for the distribution of carbon steel was found to be 1528753.4 tkm.

Life cycle inventory for transport of imported scrap for recycling at Samlo

The imported scrap of 172.445 tonnes needed to travel a distance of 33 km from Freeport to Midlands, leading to a payload distance of 5690.685 tkm.

Life cycle inventory for transport of local scrap for recycling at Samlo

From a total of 10,600 tonnes, an amount of local scrap to be transported from each district was assumed to be 1177.78 tonnes.

Table below contains the distance steel scrap has to be transported from various region to Samlo in Midlands.

Table 35: Transportation for Recycling steel at Samlo

Region	Distance (km)	Distance (tkm)
Port Louis to Midlands	31.9	37571.182
Flacq (Central Flacq) to Midlands	34.2	40280.076
Grand Port (New Grove) to Midlands	13.6	16017.808
Moka (Dagotière) to Midlands	13.7	16135.586
Pamplemousses to Midlands	34.8	40986.744
Plaines Wilhems (Curepipe) to Midlands	7.3	8597.794
Rivière du Rempart (Poudre D'Or Hamlet) to Midlands	45.8	53942.324
Rivière Noire (Bambous) to Midlands	24.6	28973.388
Savanne (Chamouny) to Midlands	28.8	33920.064
TOTAL		**276424.97**

Therefore, the total payload distance to recycle steel at Samlo was 276424.97 tkm.

Life cycle inventory for transport of local scrap for compaction

With a total amount of scrap of 4,107.838 tonnes, equal amount of 2,053.919 tonnes were assumed to be processed at both companies.

Amount of steel products transported from each district to each company = 2,053.919 / 9

= 228.2132 tonnes

Table 36 and 37 consist of distance for transportation of steel scrap to the Steel scrap Ltd and Runghen G. & Co respectively.

Table 36: Transportation for Steel Scrap Ltd

Region	Distance (km)	Distance (tkm)
Port Louis to Steel Scrap Ltd	5.55	1266.58
Flacq (Central Flacq) to Steel Scrap Ltd	37.33	8519.20
Grand Port (New Grove) to Steel Scrap Ltd	37.02	8448.45
Moka (Dagotière) to Steel Scrap Ltd	16.83	3840.83
Pamplemousses to Steel Scrap Ltd	15.85	3617.18
Plaines Wilhems (Curepipe) to Steel Scrap Ltd	23.88	5449.73
Rivière du Rempart (Poudre D'Or Hamlet) to Steel Scrap Ltd	25.29	5771.51
Rivière Noire (Bambous) to Steel Scrap Ltd	13.18	3007.85
Savanne (Chamouny) to Steel Scrap Ltd	40.99	9354.46
TOTAL		**49275.79**

Table 37: Transportation for Runghen G. & Co

Region	Distance (km)	Distance (tkm)
Port Louis to Runghen G. & Co	2.04	465.55
Flacq (Central Flacq) to Runghen G. & Co	37.5	8558.00
Grand Port (New Grove) to Runghen G. & Co	39.9	9105.71
Moka (Dagotière) to Runghen G. & Co	19.72	4500.36
Pamplemousses to Runghen G. & Co	12.33	2813.87
Plaines Wilhems (Curepipe) to Runghen G. & Co	26.76	6106.99
Rivière du Rempart (Poudre D'Or Hamlet) to Runghen G. & Co	25.55	5830.85
Rivière Noire (Bambous) to Runghen G. & Co	16.98	3875.06
Savanne (Chamouny) to Runghen G. & Co	43.87	10011.71
TOTAL		**51268.10**

For the transport of steel scrap for compaction and compression at both companies, a total of 100,543.89 tkm was covered.

The complete life cycle inventories of the inland transportation are summarised in Table 38.

Table 38: Complete LCI of inland transportation

Distribution of steel product (tkm)	**1528735.4**
Imported Scrap to Samlo (tkm)	5690.685
Local Scrap to Samlo (tkm)	292060.68
Compaction (tkm)	100543.89
TOTAL (tkm)	**1927030.655**

3.3.3.   Life Cycle Impact Assessment

The life cycle assessment of steel in Mauritius was modelled using the LCA software package openLCA 1.6.3.   A life cycle impact assessment methodology was used to calculate the environmental impacts attributed to the life cycle inventory. From the open LCA impact assessment methods, ILCD (International Reference Life Cycle Data System) 2011, midpoint v.1.0.10 was selected.

This impact assessment covered the following impact categories:-

- Acidification
- Climate Change
- Eco-toxicity
- Eutrophication
- Human toxicity
- Ionising radiation
- Land use
- Ozone layer depletion
- Photochemical oxidation
- Resource Depletion
- Respiratory inorganics

The impact assessment of the six stages within the boundary system was performed and the results are presented in Table 39.

Table 39: Impact Assessment Results of LCI

Impact Category	Unit	Steel Production (BOF Route)	Importation	Inland Transportation	Steel Recycling (EAF Route)	Compaction & Compression	Exportation
Acidification	Mole H+ eq.	9.71E+09	1.98E+08	6.15E+02	4.36E+07	1.96E+02	1.58E+07
Climate change	kg CO2 eq.	2.92E+12	4.86E+09	9.59E+04	1.31E+10	2.83E+04	3.86E+08
Freshwater ecotoxicity	CTUe	1.82E+11	1.43E+08	3.11E+03	4.34E+08	8.10E+02	1.14E+07
Freshwater eutrophication	kg P eq.	2.11E+06	1.37E+04	3.06E-01	4.19E+03	3.84E-03	1.09E+03
Human toxicity - carcinogenics	CTUh	2.82E+03	2.25E+00	5.02E-05	1.35E+01	8.67E-06	1.79E-01
Human toxicity - non-carcinogenics	CTUh	2.05E+05	1.39E+01	3.05E-04	8.94E+02	4.68E-04	1.10E+00
Ionizing radiation - ecosystems	CTUe	4.31E+05	9.65E+01	2.34E-03	3.65E+03	5.34E-02	7.68E+00
Ionizing radiation - human health	kg U235 eq.	4.36E+10	9.75E+06	2.36E+02	3.69E+08	5.40E+03	7.76E+05
Land use	kg SOC	2.19E+05	0.00	0.00	8.25E+01	0.00	0.00
Marine eutrophication	kg N eq.	1.62E+09	4.53E+07	2.89E+02	8.82E+06	2.22E+01	3.60E+06
Ozone depletion	kg CFC-11 eq.	3.62E+04	8.02E+00	1.94E-04	2.98E+02	4.46E-03	6.38E-01
Particulate matter/Respiratory inorganics	kg PM2.5 eq.	9.44E+08	6.72E+06	2.28E+01	4.74E+06	1.08E+01	5.35E+05
Photochemical ozone formation	kg C2H4 eq.	6.26E+09	1.28E+08	7.98E+02	3.12E+07	6.88E+01	1.02E+07
Resource depletion - mineral, fossils and renewables	kg Sb eq.	3.44E+09	7.77E+04	1.81E+00	1.55E+07	1.69E+01	6.18E+03
Resource depletion - water	m3	4.01E+08	5.89E+04	1.39E+00	1.36E+06	1.14E+01	4.68E+03
Terrestrial eutrophication	Mole N eq.	1.70E+10	4.96E+08	3.16E+03	8.78E+07	2.42E+02	3.95E+07

4. ANALYSIS OF RESULTS

4.1. Atmospheric Parameters

The main atmospheric pollutants, that is, airborne salinity and sulphur dioxide levels were determined for the two sites considered. More of the tests were planned. However, they could not be implemented. The results were used to categorise these parameters according to ISO 9223, as shown in Table 40. It should be noted that, referring to Table 1, the categorisation of the environments have remained the same, hence confirming the results obtained in the present study. The category for the time of wetness was taken from the results obtained for previous studies.

Table 40: Atmospheric Parameters of the site locations

Site	Average chloride deposition rate $(mg/m^2.d)$	Chloride class according to ISO 9223	Sulphur dioxide deposition rate $(mg/m^2.d)$	SO_2 class according to ISO 9223	Time of wetness class according to ISO 9223	Corrosivity category
Port Louis	71.76	S_2	35.62	P_2	T_3	3 or 4
Reduit	32.17	S_1	162.5	P_3	T_4	5

From table 40, the atmospheres at Reduit and Port Louis are expected to lie in categories 5 and 3or 4 respectively, based in ISO 9223.

4.2. Outdoor Exposure of Carbon and Weathering Steels

The graph of corrosion loss (mm) against time of exposure (months) of both carbon and weathering exposed at Reduit and at Port Louis are shown in figures 32 and 33.
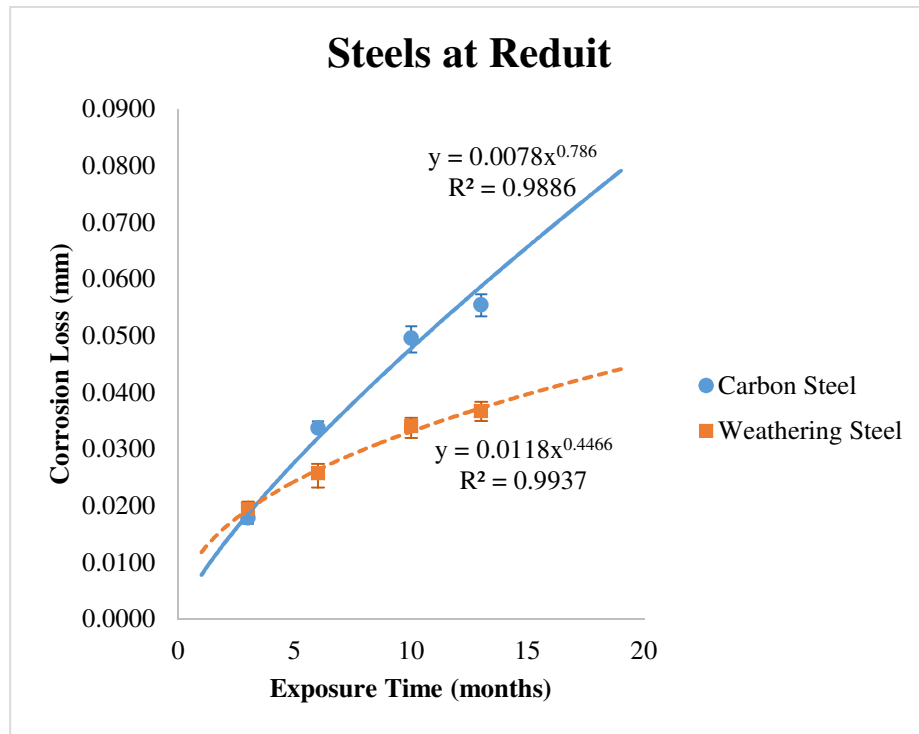
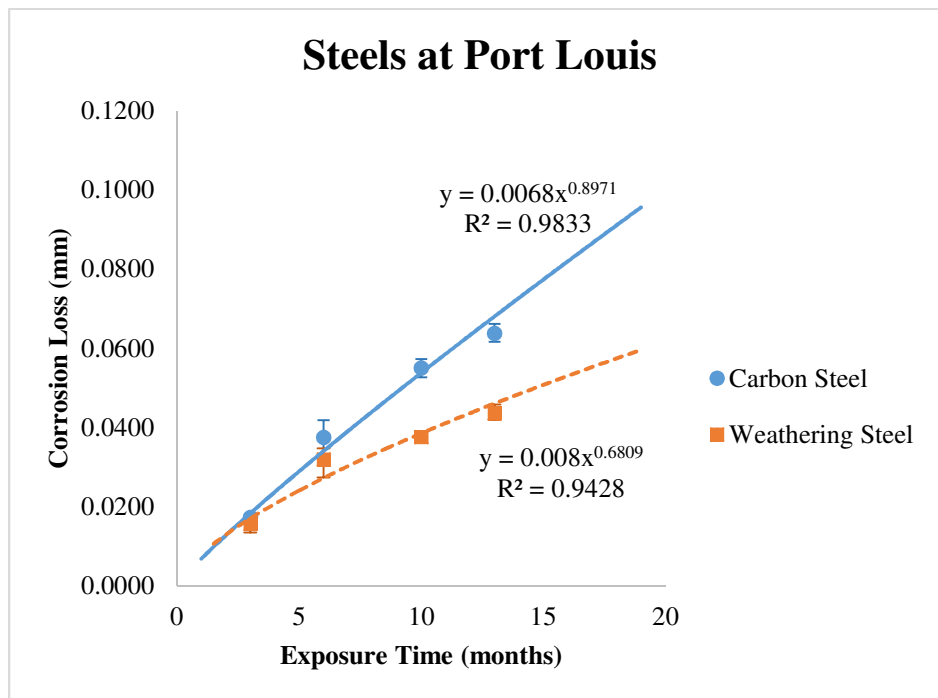**Figure 32: Corrosion Loss for Exposure at Reduit**

Figure 33: Corrosion Loss for Exposure at Port Louis

The equations of the trend curve for the corrosion losses against time of exposure are shown in Table 41. The trend curves used were of the form (Morcillo *et al.*, 2003; Feng-I Wei, 1991):

$$C = At^B$$

Where *C* is the corrosion loss in (µm) and *t* is the time (months). *A* is generally considered as a measure of the initial reactivity of the material with the environment. The exponent *B* is normally close to 0.5 when the mechanism for the corrosion reaction is ideally diffusion controlled (Morcillo *et al.*, 1993). There is no sense in B > 1, as *B* = 1 is the limit for unimpeded diffusion (high permeable corrosion products or no layer at all). Values of *B* > 1 occur practically as exceptions, due to outliers in the weight loss determinations, for example. As a rule, b < 1 (D. de la Fuente *et al.,* 2011).

Table 41- Equation of trend curves

Site	*Equation of trend curve*	
	Weathering steel	**Carbon steel**
Reduit	y= 0.118x$^{0.45}$	y=0.0078x$^{0.79}$
Port Louis	y= 0.008x$^{0.68}$	y= 0.0086x$^{0.90}$

From the equations of the trend curve, it could be observed that the exponents for the trend curves for weathering steel are much lower than those of carbon steel. The exponents also show that there is a much accelerated diffusion of the corrodants through the rust layer for carbon steel samples. The exponents for the weathering steel samples are much lower. Hence, the corrosion rate of weathering steel is expected to be lower than that of carbon steel. The calculated corrosion loss for one year of exposure and the corresponding corrosivity category for the two atmospheres are shown in Table 42.

Table 42- Corrosion loss after 12 months of exposure

Site	*Corrosion loss (mm)*		*Corrosivity category (according to ISO 9223)*
	Weathering steel	**Carbon steel**	
Reduit	0.035	0.055	*C4*
Port Louis	0.043	0.063	*C4*

It can be observed that the corrosion loss in weathering steel is 36% and 32% lower than that in carbon steel. From ISO 9223, it can be observed that both Reduit and Port Louis fall in corrosivity category C4. The atmosphere at the two sites is, therefore, categorized as high corrosivity. The level of airborne salinity at Port Louis and the level of sulphur dioxide at Reduit have ensured that their respective corrosion loss remains high.

4.3. Life Cycle Assessment of Carbon Steels

The results shown in Table 39 have been further broken down, as shown in figures 34 to 40. It can be observed that steel production is a major component contributing to the environmental and health parameters. To a lesser extent, recycling and importation of the metal are other processes having an impact on the environment and health. The results therefore recommends for greater amount of recycling which will lead to substantial reduction in kilograms of carbon dioxide equivalent as well as a reduction in the other Life Cycle Impact Assessment indicators.

The use of weathering steel will, on the other hand, lead to a substantial decrease in the import of steel in Mauritius, by approximately, one third. This will also lead to a significant reduction in the Life Cycle Impact Assessment indicators.
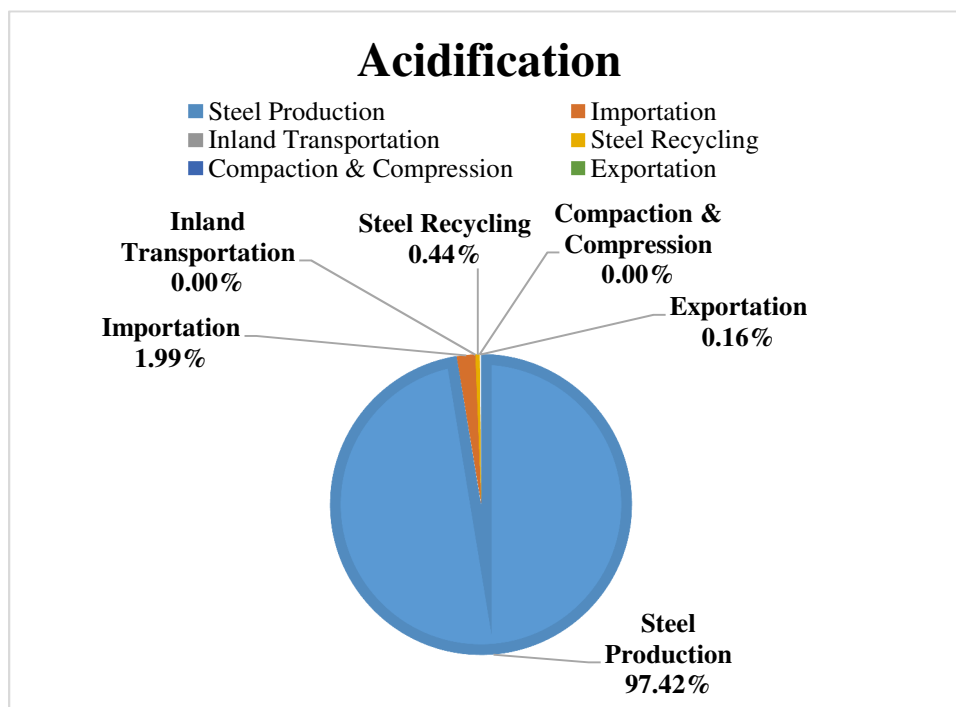

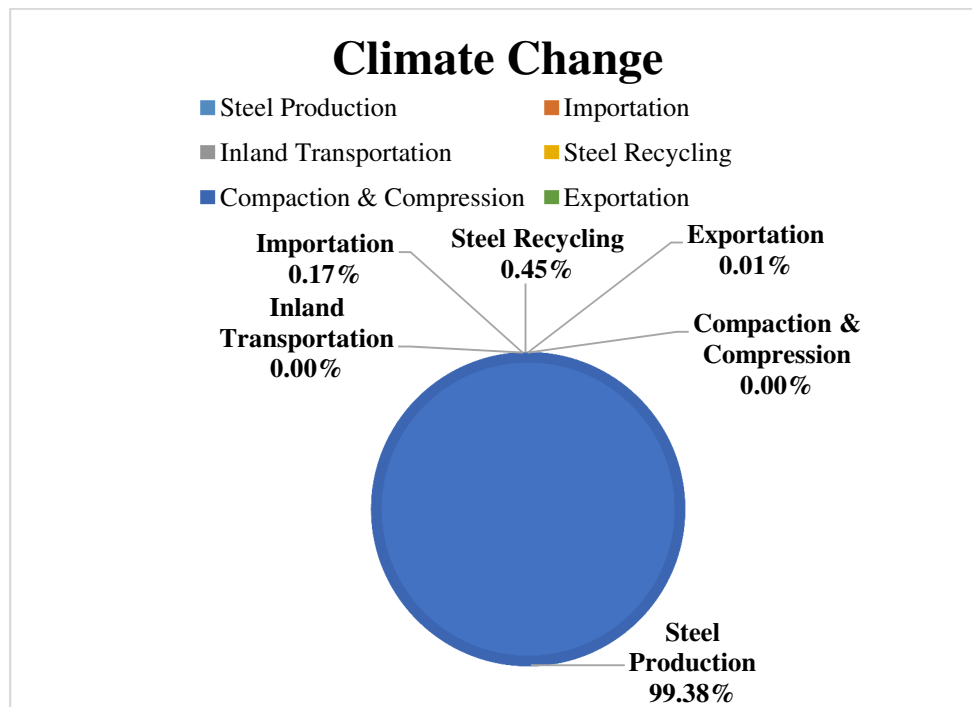**Figure 34: Process contribution for acidification**

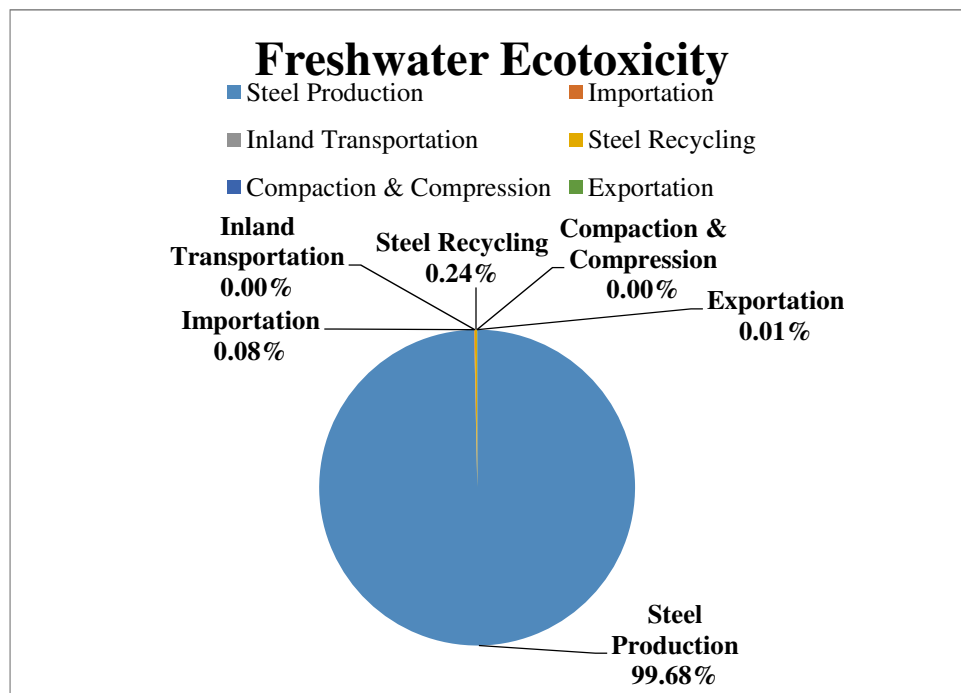**Figure 35: Process contribution for climate change**

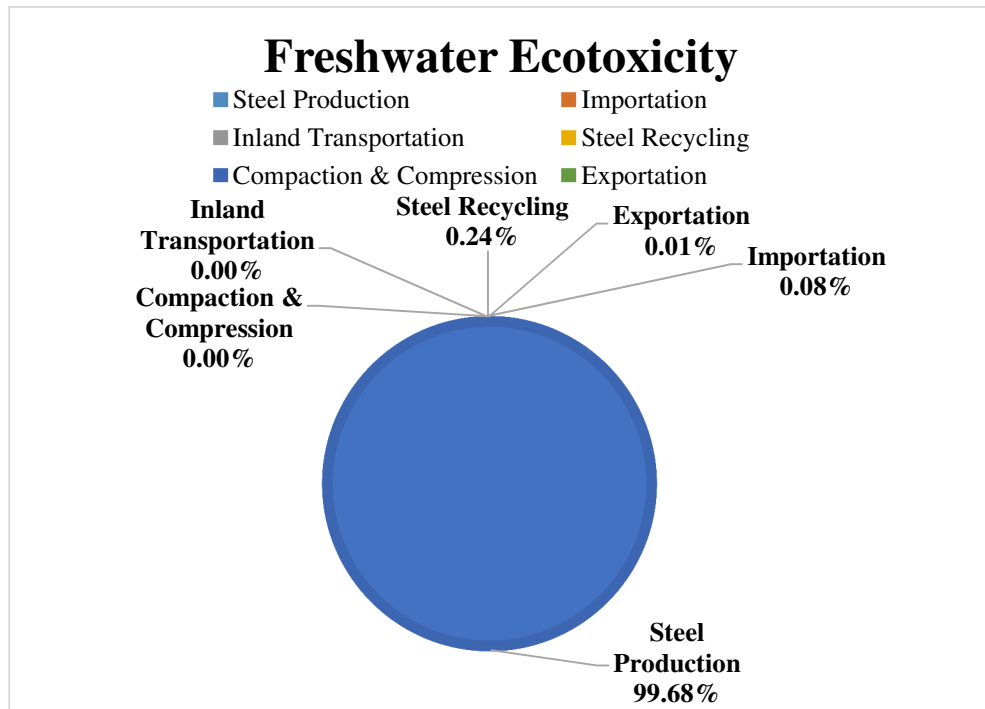**Figure 36: Process contribution for freshwater ecotoxicity**

71

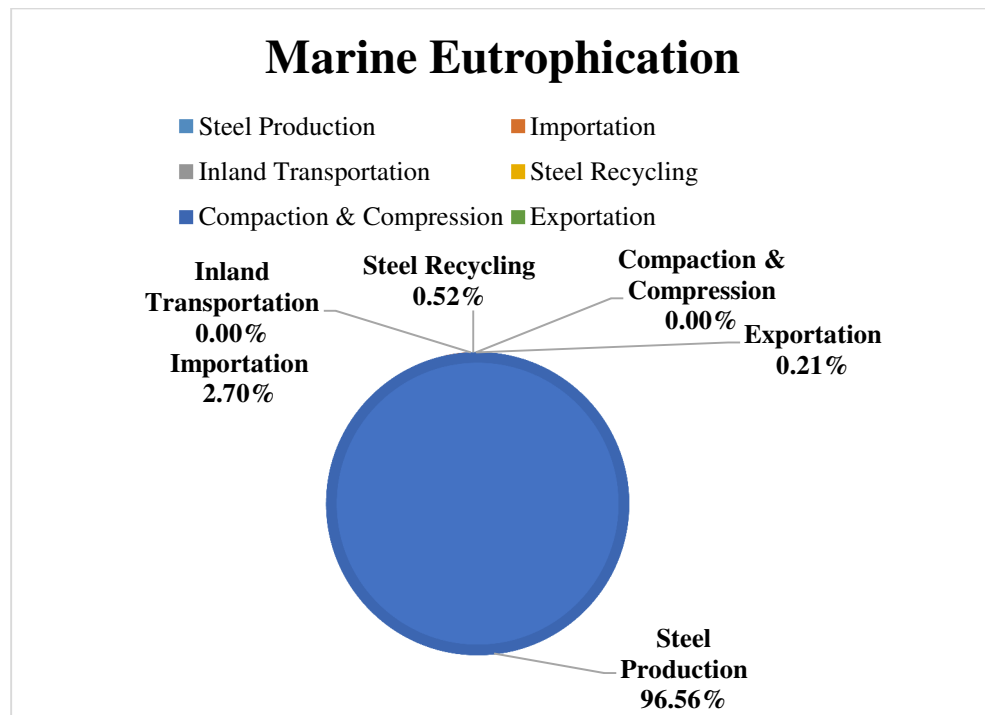**Figure 37: Process contribution for freshwater eutrophication**
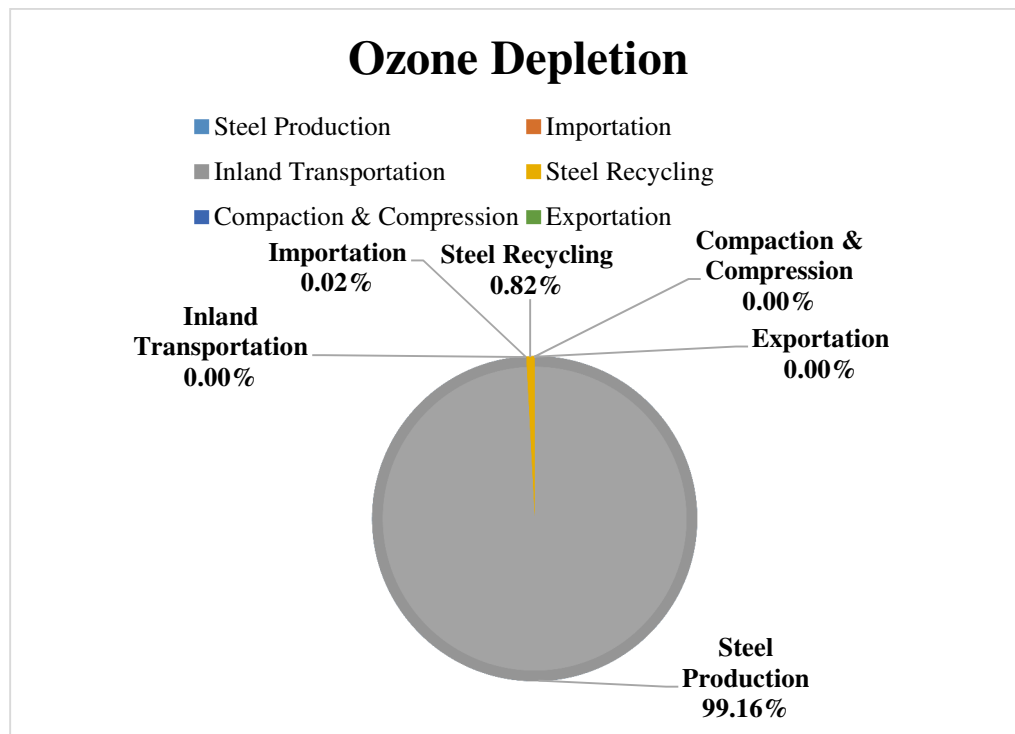

Figure 38: Process contribution for marine eutrophication

Ozone Depletion

Steel Production ■ Importation
■ Inland Transportation ■ Steel Recycling
■ Compaction & Compression ■ Exportation

Importation
0.02%

Steel Recycling
0.82%

Compaction &
Compression
0.00%

Inland
Transportation
0.00%

Exportation
0.00%

Steel
Production
99.16%

Figure 3938: Process contribution for ozone depletion

Resource depeltion- mineral. fossils and renewables

Steel Production ■ Importation
■ Inland Transportation ■ Steel Recycling
■ Compaction & Compression ■ Exportation

Inland
Transportation
0.00%

Steel Recycling
0.45%

Exportation
0.00%

Compaction &
Compression
0.00%

Importation
0.00%

Steel Production
99.55%

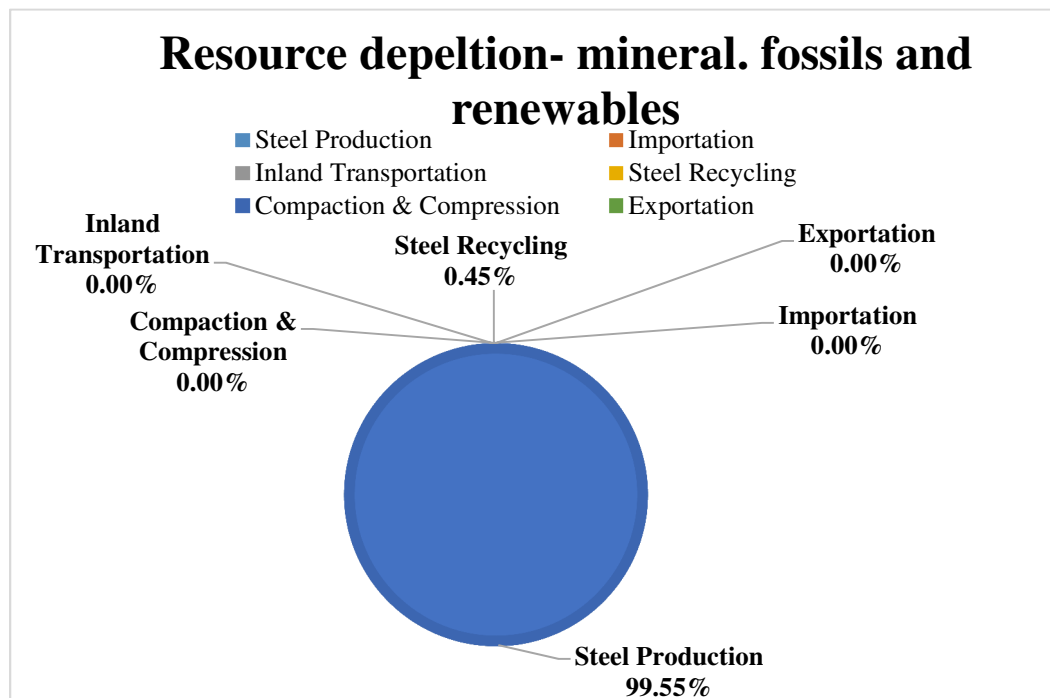**Figure 40: Process contribution for resource depletion-mineral, fossils and renewables**
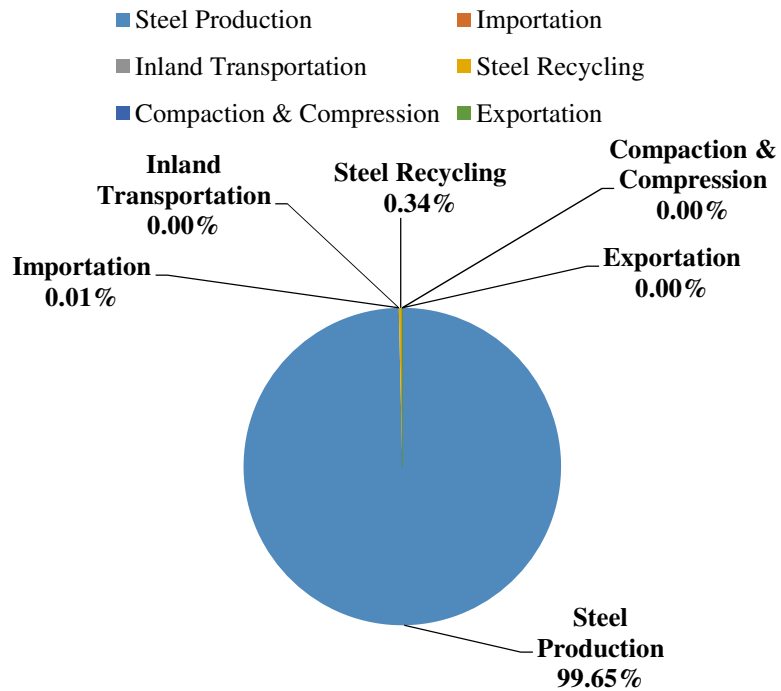
Figure 4139: Process contribution for resource depletion-water

5. CONCLUSIONS

This project was aimed to determine whether weathering steel would be a good alternative to carbon steel in Mauritius and could be used as a sustainable material in the island. This was performed through the outdoor exposure of weathering steel and mild steel to investigate whether weathering steel would be corrosion resistant in the corrosive atmosphere of Mauritius. The LCA for the use of mild steel was developed to understand the impact of the commonly used metal in the island.

It was observed that weathering steel can be successfully used in Mauritius instead of mild steel. Weathering steel has been found to corrode less than mild steel by more than 30% over one year of exposure in atmospheres falling in the C4 category, according ISO 9223.

The LCA performed from data gathered through relevant surveys in the Mauritian Industry, has shown that production of steel and its importation to Mauritius consists of the main contributors to the LCIA indicators. In fact other stages, for instance, recycling was found to have lesser impact than steel production by several orders of magnitude. In these circumstances, the use of weathering steel would provide a much better option than carbon steel, being a more sustainable material. It should be noted that the prices of both metals are approximately equal. Hence, even financially the use of weathering steel should be viable.

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