2-1-2005

Evaluation of remanufacturing as a production alternative to reduce the magnitude of environmental impacts using TRACI

Marielk del Mariano Martinez

Evaluation of Remanufacturing as a Production Alternative to Reduce the Magnitude of Environmental Impacts Using TRACI

By

Marielk del Carmen Mariano Martinez

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENT FOR THE MASTER OF SCIENCE DEGREE IN
INDUSTRIAL AND SYSTEMS ENGINEERING IN
KATE GLEASON COLLEGE OF ENGINEERING OF
ROCHESTER INSTITUTE OF TECHNOLOGY

INDUSTRIAL AND SYSTEMS ENGINEERING DEPARTMENT
ROCHESTER INSTITUTE OF TECHNOLOGY
ROCHESTER, NEW YORK

FEBRUARY 2005

COMMITTEE MEMBERS

DR. JAMES TAYLOR
ASSOCIATE PROFESSOR
INDUSTRIAL AND SYSTEMS ENGINEERING
ROCHESTER INSTITUTE OF TECHNOLOGY

DR. BRIAN THORN
ASSOCIATE PROFESSOR
INDUSTRIAL AND SYSTEMS ENGINEERING
ROCHESTER INSTITUTE OF TECHNOLOGY

Rochester Institute of Technology

This is to certify that I have examined this bound copy of a master thesis by

Marielk del Carmen Mariano Martinez

and have found that it is complete and satisfactory in all respects.

James Taylor

James B. Taylor

Signature of Faculty Advisor

14 Mar 2005

Date

Brian Thorn

Brian K. Thorn

Signature of Faculty Advisor

March 14, 2005

Date

ABSTRACT

As a result of many environmental problems associated with industrial activities and manufacturing applications, several production strategies have been evaluated to reduce the magnitude of ecological impacts. Through remanufacturing, the physical form of the product is retained along with its economic value, offering a viable option to address actual ecological problems that result from production practices. One of the instruments used to evaluate process performance and product generation is Life Cycle Assessment (LCA). However, to date, all software packages used to conduct LCA have failed to incorporate remanufacturing as a production alternative. The EPA's TRACI software package utilized in this research describes the product lifecycle in only four stages: raw materials acquisition, manufacturing, use/reuse/maintenance, and recycle/waste management. An evaluation is performed to assess the potential benefits and liabilities of incorporating the remanufacturing cycle into the production system and evaluating the importance of doing so over a range of potentially remanufacturable products. Furthermore, a case study is conducted to demonstrate that remanufacturing may represent a useful strategy for reducing the magnitude of environmental impacts related to the production of durable manufactured products. The study found that remanufacturing can reduce the amount of contributors and environmental stressors that may lead to ecological impacts. The ecological categories- 1) ozone depletion, 2) acidification, 3)ecotoxicity, 4)eutrophication, 5) global warming, 6) human health cancer, 7) human health non-cancer, 8) human health criteria, 9) photochemical smog, 10) fossil fuel use and 11) water use- evaluated by the software tool constitute the conclusion parameters to determine whether or not remanufacturing accounts for sustainability. LCA results show benefits in nine of the categories analyzed, suggesting that remanufacturing comprises a superior choice in environmental terms.

ACKNOWLEDMENT

I am grateful to the faculty members and staff of the Industrial & Systems Engineering (ISE) Department at Rochester Institute of Technology for enhancing my learning and intellectual experience.

I would like to thank my thesis advisor Dr. James Taylor for his stimulus, enthusiasm, guidance, corrections and countless support. His direction and patience were invaluable in the completion of this thesis. I would also like to thank my second advisor Dr. Brian Thorn for his expertise in the field, his significant inputs and his corrections.

Thanks to many people who have contributed to this research, specially to Jane Bare, TRACI developer, Environmental and Protection Agency (EPA) and Thom Gloria, LCA ICF consulting, for their technical assistance and for helping me to understand the LCA software tool utilized for this thesis. Thanks to Newton Green from the National Center for Remanufacturing and Resource Recovery for providing valuable information regarding cleaning technologies. I want to thank Diane Ellison, Director, RIT Part-Time and Graduate Enrollment Services for her encouragement and motivation to finish this project.

My sincere thanks and my love goes to my parents, my siblings, my family and my fiancé for their unconditional support and encouragement to complete this goal.

Also, I want to thank some current graduate students of the ISE department that have greatly support me with their incentive through the length of this research: Jessica Pena, Laura Modesto, Carlos Plaz, Ike Vanderhorst, Guillermo Lopez, Alicia Polanco and everyone else.

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ACRONYMS

AL	Aluminum material
AoP	Endpoint
BTU	British Thermal Unit
CNC	Control Numeric Machines
C	Coal
CAS	Chemical Abstract Service
DALY	disability-adjusted life-years
DP	Core Drop-off
DFE	Design for the Environment
EF	Fossil fuel based energy
EPA	Environmental Protection Agency
ER	Renewable Energy Sources
ETP	Ecological Toxicity Potential
GW	Global Warming
Feedstock	Energy used for non-fuel purposes
FD	Final Distribution
ICF	International Coach Federation Consulting
ISO	International Organization for Standarization
Kwh	Kilowatt hour
Kg	Kilogram
L	Litter
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
Man	Manufacturing
MA	Manufacturing & Assembly
MJ	Mega Joule
MP	Material Processing
Ng	Natural Gas
NCR^3	National Center for Remanufacturing and Resource Recovery
O	Oil
PM	Particulate Matter
PVC	Polyvinyl Chloride material
Rem	Remanufacturing
RMC	Remanufacturing Center
RCC	Recycling Center
RMA	Raw Material Acquisition
ST	Steel material
VOC	Volatile Organic Compounds
TRACI	Tool for the Reduction and Assessment of Chemical and other Environmental impacts
WP	Water pump

1. INTRODUCTION

Increasing costs for waste disposal and increasing public demand for environmental quality are forcing industries to reduce and eradicate unfavorable environmental impacts attributable to the manufacture of products. The environmental performance of products and processes has become a major issue in recent years for companies and governments as a result of several environmental problems- including Ozone Depletion, Smog, and Human cancer- associated with activities performed within the manufacturing sector such as material extraction and product fabrication. Finding solutions to address these issues is not an easy task, and companies need new tools to help them meet the challenges they will face in the future. Most industries and ecological organizations around the world are using major environmental laws- including the National Environmental Policy Act (NEPA), Pollution Prevention Act (PPA), and the Occupational Safety and Health Act (OSHA)- to confront sustainability concerns. The objectives of these kinds of legislation are: 1) to help manufacturers analyze their processes and improve their products and 2) to monitor and quantify the ecological impacts leading to environmental degradation.

Clearly, providing our society with goods and services contributes to resource depletion, and the consumption of natural resources might occur at any stage in a product's life cycle, ranging from raw material extraction through ultimate disposal. Major ecological impacts such as Global Warming, Acidification, and Eutrophication, are among the detrimental effects included in the countless lists of damages that our environment is experiencing as a result of unfavorable manufacturing practices and disposal strategies. To control these negative effects, many companies have responded by creating "greener" products and using "greener" processes; that is, by identifying production mechanisms where improvements can be made to benefit the environment. As manufacturers become more environmentally conscious, they tend to investigate various methods of producing their goods in such a manner as to reduce the environmental harm, while simultaneously maintaining low costs. For that reason, industrial policies and programs are being developed with the objective of designing green products. One of the fields that focus on environmental problems is Industrial Ecology often referred to "the science of sustainability". This approach redefines the role of industry in reducing environmental concerns, requiring that manufacturers try to understand all the implications of industrial systems, adjusting those systems toward sustainability.

One widely known related topic addressed by industrial ecology is Design for the Environment (DFE), which incorporates the idea of designing products taking into account the production activities involved in the manufacturing process to make them more environmentally friendly.

In order to evaluate an industrial system's performance and its environmental impacts, Life Cycle Assessment (LCA) has represented an essential tool to conduct a detailed examination of different products/processes life cycles. LCA has been widely used in many industries as a powerful instrument to enable manufacturers to quantify how many resources are being consumed as well as the environmental implications involved at each stage during product manufacture. In addition, LCA helps companies to determine areas where improvements can be made and to select processes and products that result in the least impact in environmental terms. LCA is increasingly gaining acceptance across manufacturing companies. The International Organization for Standardization (ISO) has begun to develop principles and guidelines for conducting an accurate LCA. However, one of its major limitations lies in the subjectivity of the final outcome caused by different and contradictory conclusions about similar processes and products. Accordingly, a great deal of work is currently being conducted on LCA to create standardized methods of interpreting data results, including the creation of LCA software. These software tools are capable of running a life cycle assessment in a most precise way, reducing the chance of subjective judgments and effectively handling the extensive amount of data required for accurate analysis.

Currently, LCA considers remanufacturing as one of the waste management alternatives that appears to be a feasible choice to reduce waste and to reduce durable products occupying landfills. Remanufacturing and product recovery have been receiving increased attention in the past decade with the awareness of environmental concerns also increasing. However, many industrial tradeoffs- including uncertainty in material recovery, efficient disassembly techniques, and the need to balance returns with demands- must be evaluated before adopting remanufacturing as the best solution for environmental degradation and product disposal. Investigational and experimental study is required to understand the potential benefits of incorporating remanufacturing in TRACI and/or other LCA software packages.

1.1 PROBLEM STATEMENT

Current approaches of environmental life cycle assessment rely to a large extent on software tools to make the process more efficient. Available software tools utilize a number of different protocols for performing such assessments. Tools like "SimaPro" and EPA's TRACI package take a process orientation while other tools like "Eco It" takes a product bill of materials approach in order to conduct the assessment. All assessment tools access a predefined database to extract the environmental impacts associated with the implementation of various processes or the generation of various products. Currently the EPA's TRACI tool is the only widely available tool that incorporates a US appropriate data set.

Most LCA software tools available on today's market rely on a fundamental model for the product life cycle, and are designed to assess all the inputs and outputs of a product. According to the Environmental Protection Agency (EPA) the typical model for a product life cycle consists of the following four stages: *1) Raw Material Acquisition, 2) Manufacturing, 3) Use/Reuse/Maintenance and 4) Recycle/Waste Management.* TRACI software was created under the same principle, based on these four stages. One of the TRACI limitations is that the software does not allow any modification of the life cycle stages that are built into the package. Nowhere in TRACI is there an explicit opportunity to incorporate remanufacturing as a production strategy.

In this research the possibility of incorporating remanufacturing cycle as one of the stages into the TRACI software's package will be studied, with the objective of analyzing and demonstrating some of the contributions of remanufacturing as a production alternative in environmental terms. A remanufacturing approach to product delivery may be a useful strategy for reducing the environmental impact associated with the production of durable manufactured products.

1. BACKGROUND

1.1 Overview

This chapter reviews the basic concepts on which this research is based. Given the fact that this study focuses on the integration of different components such as the incorporation of remanufacturing into TRACI's software, several definitions are explained in detail. The first section discusses the development of the remanufacturing industry and its impact on the US economy over the past 25 years. Various principles and fundamentals of the remanufacturing industry are explored. The second part provides information about Life Cycle Assessments (LCA) and the main characteristics of the LCA software package "TRACI", being used to perform the experiment. Lastly, a summary is provide regarding the environmental categories evaluated by the software package to understand the environmental stressors capable of damaging the ecology.

2.1.1 Remanufacturing Industry

The Remanufacturing Industry began during the Depression and gained momentum during World War II, when raw materials such as steel were one of the most used materials in the war effort. Weapon systems and military equipment were commonly remanufactured to save on the cost of acquiring new ones. Since then, the remanufacturing industry has enjoyed steady growth. Remanufacturing is considered to be another form of reuse, a key waste prevention strategy. "Remanufacturing is a little-known industrial activity that is economically and ecological significant in the United States" (Lund, 1996). Many studies and experts estimate that annual sales from 73,000 US firms involved in remanufacturing total approximately $ 53 billion, employing about one-half million people across the country. "This industry that requires only small capital investments and relatively low skilled people has the potential for re-introducing industrial type jobs and wages into urban areas where people are underemployed or unemployed" (Hauser and Lund, 2003).

The report "Environmentally and Energy-Conscious Cleaning Technologies for Automotive Parts Remanufacturing in New York State" prepared for the NCR[3] remarks that remanufacturing automotive parts conserves an estimated 85 percent of the energy used in making new products. It also reduces air pollution by keeping metal out of the re-smelting process. In 1996, Lund describes the remanufacturing industry as an unappreciated and unrecognized sector similar to a "Hidden Giant" with a great diversity of products, company sizes and locations. With support from the Argonne National Laboratory, a team of researchers at Boston University under the direction of Professor Lund, established a database of 9,903 american remanufacturers. Although the estimates are far from precise, the data suggest the following.

- Total Number of firms — 73,000
- Total Annual Industry Sales — $53 billion
- Total Direct Employment — 480,000
- Average Annual Company Sales — 2.9 million
- Average Company Employment — 24
- Number of Product Areas — Over 46 major categories

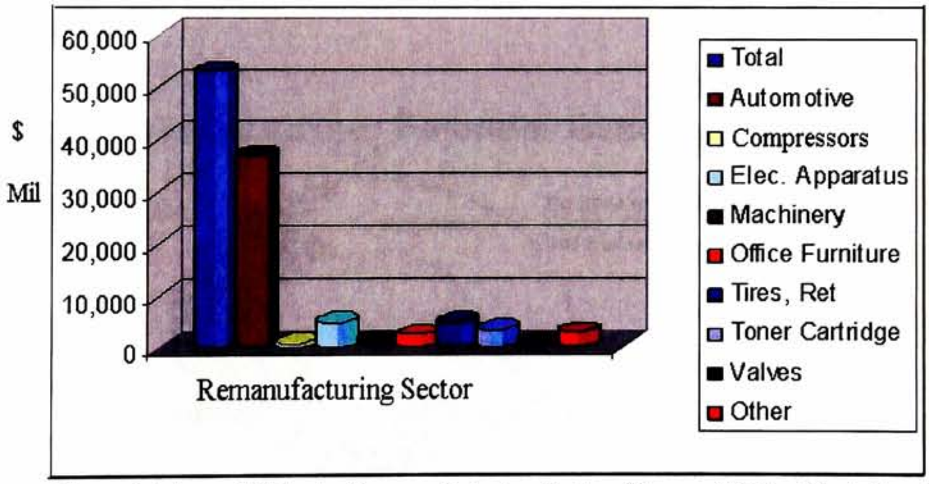


Figure 2.1 Annual Sales by Remanufacturing Sector. (*Source:* Hidden Giant, Lund 1996)

The report also provides economic information on eight sectors of the remanufacturing industry: automotive, compressors, electrical apparatus, machinery, office furniture, tires, toner cartridges, and valves (fig 2.1). As an example of the analyses presented by Lund, this graphic above shows the range of sales per industry sector.

Toussaint (2000) in the article "Remanufacturing :The Original Recycling" reported that the entire remanufacturing industry generates approximately $65 billion in sales, with the automotive segment representing $37 billion of that total, which is equivalent to 57% among all industries.

Remanufacturing is also an environmentally and economically way to achieve many of the goals of sustainable development. Remanufacturing focuses on value-added recovery, rather than just material recovery. A major benefit is that the energy used to remanufacture products is certainly less than the energy needed to make new and/or recycled products. In addition, extending the useful life of consumer products and industrial equipments saves disposal costs and simultaneously decreases materials going to landfills, incinerators, and recycling facilities. The European Journal of Operational Research in the publication "On the widget remanufacturing operation" remarks that remanufacturing represents the combination of the three R's- reduce, reuse and recycle- into a single activity, emphasizing that the remanufacturing process has some of the same requirements as recycling, such as an efficient collection system.

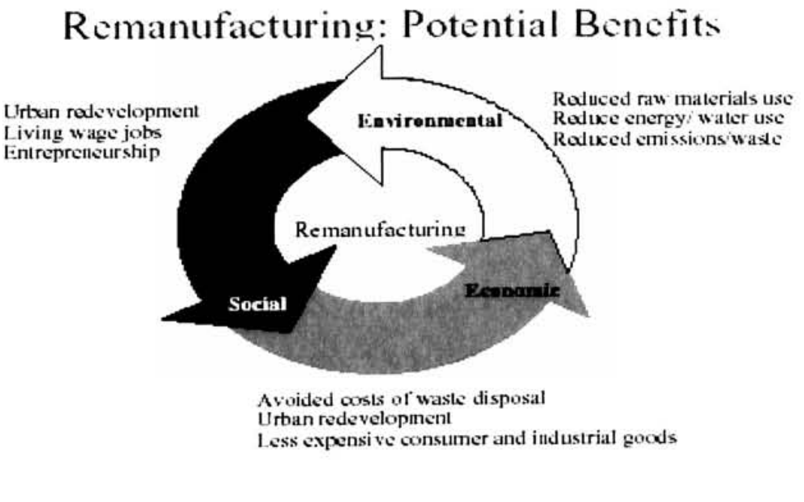


Figure 2.2 Remanufacturing benefits. (Source: http://www.tellus.org/b&s/newsletters/envpers15.pdf)

As shown in the graphic above (fig 2.2) the benefits of remanufacturing go beyond the environmental concerns and contribute positively to the social and economic sector as well.

Some of the remanufacturing contributions identified by Lund in his study "An American Resource, 2003 " include material and energy conservation, plant and equipment conservation, employment in the domestic economy, industrial skill training, lower prices which broaden product markets, and safe disposal of hazardous materials. Despite all the positive points that a remanufacturing option can have when compared with other disposal alternatives, remanufacturing also has additional requirements that often are overlooked by those promoting its environmental advantages. For example, additional packaging and transportation may be necessary to return products for remanufacturing. Energy, water, appropriate equipment, and chemical agents are also required during the cleaning process within remanufacturing.

2.1.2 Remanufacturing Process

In simple terms "Remanufacturing" is the process of disassembly of products during which parts are cleaned, replaced and then reassembled to meet original standards. Lund (1998) has identified 75 separate product types that are routinely remanufactured, and has developed 7 criteria for remanufacturability. The seven criteria are:

1) The product is a durable good
2) The product fails functionally
3) The product is standardized and the parts are interchangeable
4) The remaining value-added is high
5) The cost to obtain the failed product is low compared to the remaining value-added
6) The product technology is stable
7) The consumer is aware that remanufactured products are available.

Remanufacturing begins with the reclamation of used durable products. Typically called "cores". These components are then disassembled into parts, which are cleaned, inspected, and tested to determine whether they meet acceptable quality standards to be reused. Some parts become waste while others that do not meet standards can be repaired or reconfigured. These used parts and some new ones are then combined to reassemble the original core from which they were reclaimed, or to build a product with a new identity. Remanufactured products typically have the same or similar performance characteristics and quality standards as new units. The following illustration (figure 2.3) support the previous explanation about the remanufacturing process.

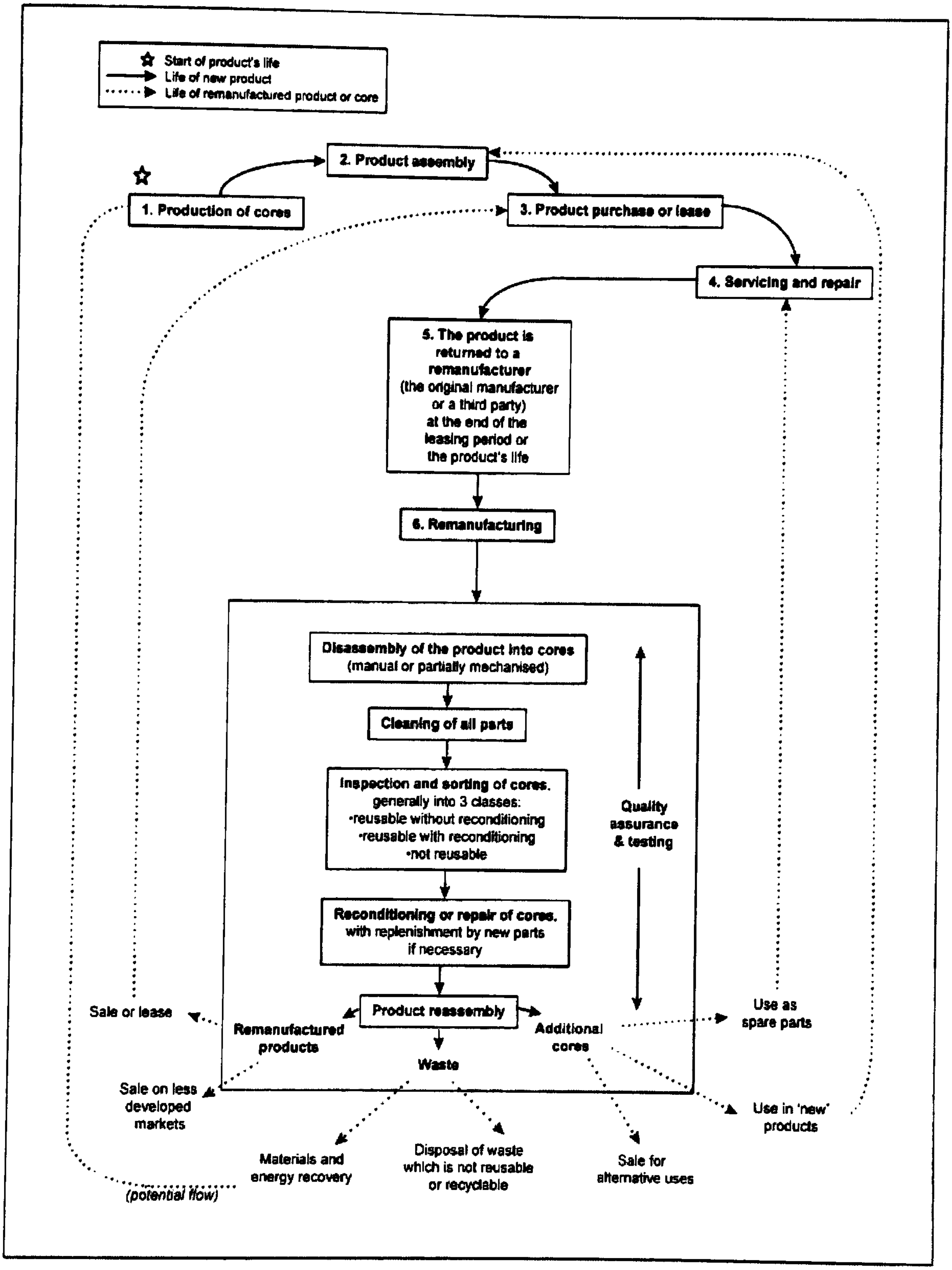


Fig 2.3 -A generic remanufacturing process /Source: Journal of Cleaner Production 9 (2001)

Before the processing step in a remanufacturing system, it is necessary to determine the best way to re-capture the cores and parts to be remanufactured. Disassembly is the first step in the remanufacturing process, acting as a gateway for parts to go to the different stages of the remanufacturing cycle. In general, disassembly operations are highly variable with respect to the time required. Some statistics report that disassembly times ranged from minutes to weeks, with large variances in required time to disassemble large units. After disassembly and breaking down the product components, new parts must replace all parts that are not recoverable. Routings and processing times must be established because part's condition will not be known until a unit is disassembled, cleaned and eventually inspected. The operation required for each part may vary due to conditions such as different age, wear and operating capability of the unit.

As a result, bottlenecks are common in this environment because material recovery from disassembly will vary from unit to unit affecting other issues such as time, volume, variability, and scheduling. The processing time required for the remanufacture of a part is also a random variable dependent on the condition of the part. In addition, disassembly operations have been examined extensively from an economic point of view. Certainly, the effects of disassembly operations may impact many production areas including production control, floor control, scheduling, and materials planning. Therefore, disassembly requires a high degree of coordination with reassembly in order to avoid massive inventory levels and poor customer service. In many industries, firms have implemented pilot disassembly facilities to learn efficient ways of dealing with end-life products, e.g., (vehicles). That is because the profitability of a remanufacturing operation depends on the value recovered from the used products.

Cleaning is a crucial aspect of remanufacturing. If a remanufactured product is not adequately cleaned, it can unfavorably affect the future product performance and also may fail the customer's aesthetic expectations. In most cases, surface cleaning represents a significant percentage of the cost of remanufacturing a product. As a result, one of the more important aspects facing remanufacturers is to identify quick and inexpensive cleaning procedures and technologies.

Another complicating characteristic is the inadequate correlation between demands and returns. This condition is extremely related and dependent on the uncertainty of time to process cores and parts to be remanufactured. A make-to-order remanufacturing shop will have little need to balance core acquisition with demand, since the product must be returned before the work may start. On the other hand, in a make-to-stock environment, core acquisition and timing is a conflicting concern that should be addressed in a careful way.

A factor that might increase the complexity level in a remanufacturing facility is the serial number specific reassembly operations. This coordination may be difficult to achieve when a unit is composed of a serial number specific part and/or component. This requirement may be customer-driven, i.e. when a customer turns in a part to be remanufactured and then request the same part unit be returned to them. This requirement is common when referring to large and heavy equipment such as car engines, and also where there is a need to ensure system reliability of mechanical assemblies as in the aircraft industry.

The types of products being remanufactured vary, generally falling into two classes: capital goods and consumer durable goods. Capital goods range from complex military weapon systems, to manufacturing, mining, and agricultural equipment to vending machines. These capital goods constitute the majority of the remanufacturing expenditures in the United States. When talking about consumer goods, process costs can often exceed the price of new product, which has limited their use in many industries. There are, however, some prominent examples of successful remanufacturing of consumer durable goods including automotive parts, computers, laser toner cartridges, and single-use cameras.

2.1.3 Remanufacturing Implications

Some of the common implications that organizations have to consider when thinking about remanufacturing are:

1) The specialized equipment involved in the process, such as cleaning, and test equipment, and optical gauges.
2) The information technology suppliers and resources to support remanufacturing and distribution process activities.
3) Design engineers who develop design optimization tools for the remanufacturing processes of disassembly and reassembly.
4) Third-party logistics suppliers, since they would experience a large increase in reverse logistics activity.

Two major concerns affecting the remanufacturing industry are : 1) "Return the Flow" regarding the material recovery and the strategies design to re-capture the product, and 2) "Design for Remanufacturability" which means that most products arriving at the end of the first useful life cycle are not actually designed for remanufacturing. Thus, seven complicating characteristics have been identified within the remanufacturing industry. These are outlined in the following table, and the corresponding explanation for each is presented after the table.

Complicating Characteristics	**Forecasting**	**Logistics**	**Scheduling/ Shop Floor Control**	**Inventory Control /Management**
1) The uncertain timing and quality of returns	✓	✓	✓	✓
2) The need to balance returns with demands				✓
3) The disassembly of returned products			✓	✓
4) The uncertainty in materials recovered from returned items			✓	✓
5) The requirement for a reverse logistics network		✓		✓
6) The compilation of materials matching restriction			✓	
7) The problems of stochastic routings for materials and highly variable processing time			✓	

Table 2.1 The complicating 7 characteristics of remanufacturing (Guide 2000)

The issues contained in each one of these complicating categories are detailed below.

1) Uncertainty in timing and quantity of returns:

    Forecasting models to predict returns rates and volumes

    Reliability models to better predict life-cycles for product with multiple lives

    Method effectiveness in reducing the unknown time and the quantity of returns

    Tracking technology advances that influences product returns

2) Balancing returns with demands:

    Methods to evaluate the benefits of synchronizing returns with demands

    Product positioning strategies to serve multiple markets

    Aggregate production planning that include returned products

    Coordination about inventory and product purchase in order to control return rates

3) Disassembly of returned products:

    Models to plan what parts and components to recover in disassembly

    Models and methods that examine the effectiveness of coordinating disassembly release with reassembly

    Models for the design, layout and staffing of disassembly facilities

4) Material recovery uncertainty:

    Studies examining the key differences between traditional purchasing activities and purchasing for remanufacturing

    Models that can predict amount of recovered material based on age of product and usage rate

    Studies examining the use of MRP, including modifications/suitability

5) Reverse logistics:

    Models and systems for core acquisition management and strategies

    Optimal channel choice for remanufacturing

    Studies that can establish product recall strategies management and strategies

    Studies about the differences between material reuse logistics and product reuse logistics

6) Materials matching:

    Information systems to aid in material tracking

    Models and systems that provide visibility for materials requirements

    Remanufacturing lot sizing explicitly considering materials matching restrictions and policies

    Models and systems for shop floor control coordination

7) Stochastic routings and variable processing time:

- Models that provide for scheduling coordination between disassembly and reassembly
- Bottleneck scheduling heuristics based on cleaning operations
- Order release methods that consider the rapidly changing workloads in remanufacturing work centers
- Remanufacturing lot sizing models that consider the trade-off between set-up delays and unnecessary processing delays
- Order release methods that consider the rapidly changing workloads in remanufacturing work centers.

2.1.4 Advantages and Disadvantages of Remanufactured products

Giuntini, (2003) in his article "Remanufacturing: The next great opportunity for boosting US productivity." remarks that one of the major advantages of remanufacturing is that a remanufactured product brings lower prices to the consumer, typically on the order of 30 to 40 percent less than similar new products. It also means more consumer choice, especially for obsolete and discontinued products that are not easy to find in the market anymore.

One obstacle lies in the fact that customers often may consider a remanufactured product inferior as compared to a new product. This factor makes difficult the fair competition between remanufacture products vs. new product in the aftermarket. As a way to manage this issue, a common strategies used by remanufacturers is to include extensive warranties in remanufactured products to enhance consumer confidence. In today's competitive marketplace, consumers have a broad range of products to choose to meet their needs, along with a corresponding wide range of prices. Overall however, society benefits more from remanufactured products, with significant energy savings over the production of new products and the associated reduction in the use of scarce natural resources. "Every time a part is reused, all the energy and emissions that were produced in its manufacturing and the processing of its materials are salvaged" Navin-Chandra, (1993).

2.2 Life Cycle Assessment Background

Life cycle assessment (LCA) is a system in which the inputs and the outputs of an activity are systematically identified and quantified; from the extraction of raw material from the environment to their ultimate disposal back into the environment. LCA enables manufacturers or any person conducting that kind of research to determine and quantify how much energy and raw materials are used and how much solid, liquid and gaseous waste is generated at each stage of the product's life. LCA evaluates all stages of a product's life cycle from the perspective that all operations are interdependent, meaning that one process leads to the next. When conducting an LCA, the design and development phase is usually excluded since it is often assumed that its contribution is not significant. However, one has to note that the decisions in the design/development phase highly influence the environmental impact in product manufacture and other life cycle stages as well, meaning that the design of a product strongly predetermines its behavior in the subsequent phases.

The process of conducting a complete and detailed examination of the life cycle of a product/process is fairly recent. LCA is still a new and growing application, with its roots in research related to energy requirements in the 1960's. The necessity for these kinds of studies has emerged in response to increased environmental awareness from government and industry as well as the general public. ISO 14040 defines Life Cycle Assessment as follows: LCA is a technique for addressing the environmental impacts and potential impacts associated with a product by:

1. Compiling an inventory of relevant inputs and outputs of a product system;
2. Evaluating the potential environmental impacts associated with those inputs and outputs;
3. Interpreting the results of the inventory analysis and impact assessment phases in relation to the objective of the study.

Different terms have been used to describe the processes. One of the first terms used was *Life Cycle Analysis,* but more recently two terms have come to replace the first one. Those are: *Life Cycle Inventory* (*LCI*) and *Life Cycle Assessment (LCA).* Other terms such as *Cradle to Grave Analysis, Eco-balancing and Material Flow Analysis* are also used. Regardless of the name used to describe it, LCA is a potentially powerful tool that can assist a regulator to formulate environmental legislation. At the same time LCA helps companies to identify changes in their operations, including product design, which can lead to environmental benefits, cost savings and broader customer choices.

The LCA originated when it became clear that the only sensible way to examine industrial systems was to evaluate their performance. This approach attempted to assess the resource cost and to evaluate the environmental implications of different patterns of human behavior. Later, LCA became essential to support the development of eco-labeling schemes, which are operating or under development in many countries around the world. That is because for eco-labels to be granted for certain products the authorities need to evaluate the manufacturing process involved, the energy consumption in manufacture and use, and the amount and type of waste generated (environmental load) . Although LCA was initially developed as a tool for investigating the environmental impacts of products, more recently considerable interest has been shown in applying the LCA technique to waste management systems. Waste management sub-systems include collection, transport, separation, treatment and final disposal of residues. LCA involves making detailed measurements during the manufacture of a product, from mining of the raw material used in production and distribution, to its use, possible reuse, recycling, and its eventual disposal.

2.2.1 LCA Process

The Environmental Protection Agency (EPA) indicates that LCA process consists of four major components:

1) Goal Definition and Scoping: describe the product, process or activity. Establish the context in which the assessment is to be made and identify the limits and environmental effects to be evaluated.

2) Inventory Analysis: identify and quantify energy, water and material usage and environmental releases (e.g., air emissions, solid waste disposal).

3) Impact Assessment: assess human and ecological effects of energy, water and material usage and the environmental releases identified in the inventory analysis.

4) Interpretation: evaluate the results of the inventory analysis and impact assessment to select the preferred product; product or service with a clear understanding of the uncertainty and assumptions used to generate the results.

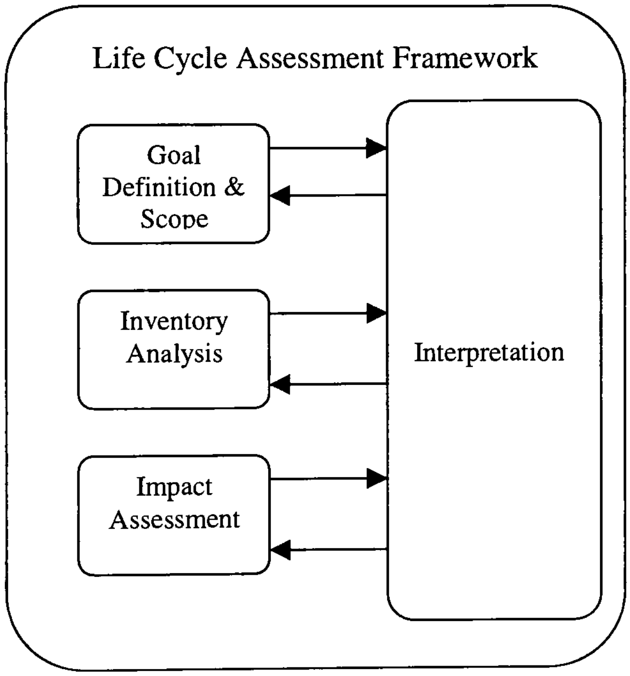


Figure 2.4 Phases and applications of an LCA. (Based on ISO 14040, 1997)

In basic terms, three main steps are involved in these types of studies. The first step is the *collection of the data* and the second is the *interpretation of that data previously collected*. The collection of the data is a lengthy and meticulous exercise and can be complicated. For that reason, it is important to set and clearly define the boundaries and restrictions of the study.

Having compiled the detailed inventory, the next step should be to evaluate the findings. This stage is more difficult, since it requires interpretation of the data and value judgments. The last stage is the *improvement* step in which the system is modified in some way to reduce or ameliorate the observed environmental impacts.

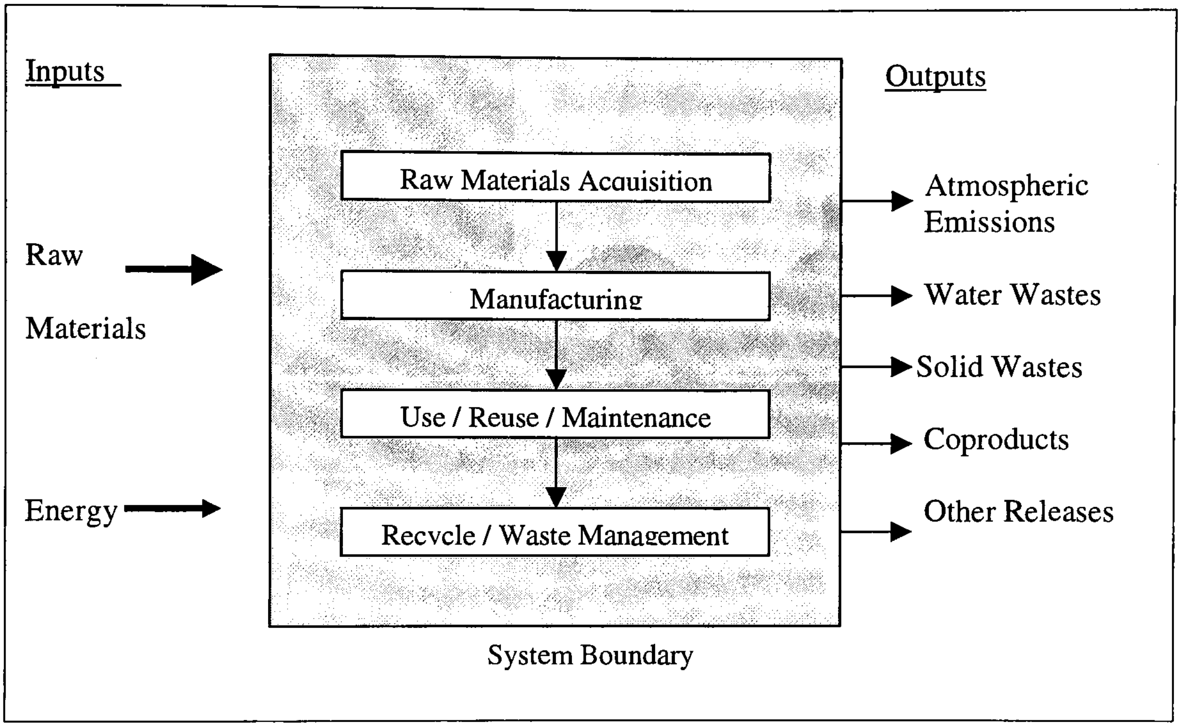


Figure 2.5 Life Cycle Stages (Source: EPA, 1993)

Figure 2.5 illustrates the possible life cycle stages that can be considered in the traditional LCA and the typical inputs/outputs measured.

2.2.2 Controversial LCA Stages

Besides the normal LCA stages that can be observed in the graphic fig 2.5 , *Recycling* represents a stage that may be difficult to incorporate into the LCA calculations. That is because materials like steel and aluminum can technically be recycled an indefinite number of times. Also, paper can be theoretically reprocessed four or five times depending on the fiber resistance. As a result of these inconsistent conditions, the accuracy of the results may be a major concern. Thus, such factors may affect the calculations and the final outcome of the analysis.

On the other hand, remanufacturing is most often not considered as one of the stages of the typical LCA. Currently, the NCR[3] is one of the few institutions that is including the remanufacturing stage as one of the alternatives after the retirement phase of any product.

Life-Cycle of a Product

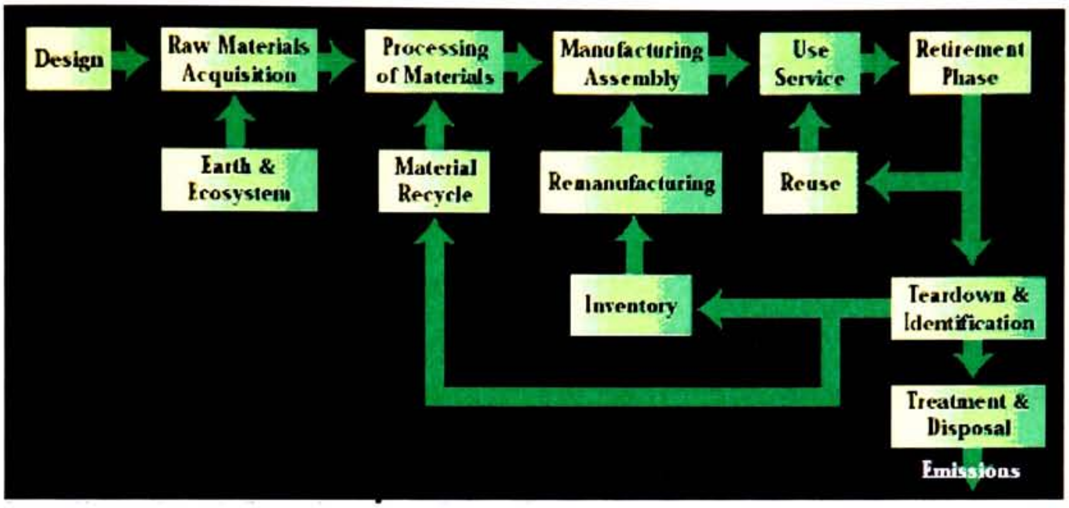


Fig 2.6 Extended life cycle model (Source: National Center for Remanufacturing and Resource Recovery).

This Figure 2.6 illustrates an "Extended life cycle model" where remanufacturing appears as one of the stages to manage products before ultimate disposal. The article "Recyling V Remanufacturing" by Tricia Judge (Sept 1998) reports that Dr. Nabil Nasr, director of the NCR[3] in Rochester, NY, firmly believes that remanufacturing is far superior to recycling for several reasons. He explains that "Remanufacturing is a perfect example of how economic development and environmental protection can work hand in hand. When compared to the widely accepted recycling, remanufacturing is far superior environmentally and economically speaking

2.2.3 LCA Contradictions/Limitations

In terms of limitations, performing a LCA can be time intensive. Depending upon how the users wish to conduct the assessment, gathering the data can be problematic and the availability of data can greatly impact the accuracy of the final results. Many LCAs have reached different and even sometimes contradictory conclusions about similar processes and products.

Comparisons are rarely easy to make because of the different assumptions that can be used in the analysis. However, a great deal of work is currently being conducted on this aspect of LCA to create standardized guidelines and methods for interpreting the data, including the creation of LCA software. Life Cycle Analysis must be used cautiously concerning the interpretations of the inventory data.

When first conceived, it was predicted that LCA would enable definitive judgments to be made. That belief has now been discredited. In most situations by using LCA it is impossible to prove conclusively that one product or process is better than any other. Perhaps it would be more "environmentally friendly" to show where a better sustainable product/process could be substituted. Major concerns about previous LCA done for many companies include the fact that some institutions want to preserve the confidentiality of the sources where the data were collected. It is also understandable that some industries never make their assessments public because that information may indicate that their own product is somehow inferior to that of a competitor. In the worst case, this kind of information may reveal that their processes and chemical emissions are violating environmental legislation established for ecological organizations.

From a business perspective, LCA and DFE can help improve a product's market competitiveness. DFE helps develop "green" products that may enjoy preferential pricing in public procurement processes or may have additional appeal to customers. Some companies have found DFE valuable as a tool for stimulating innovation above and beyond environmental benefits.

2.3 TRACI

Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts

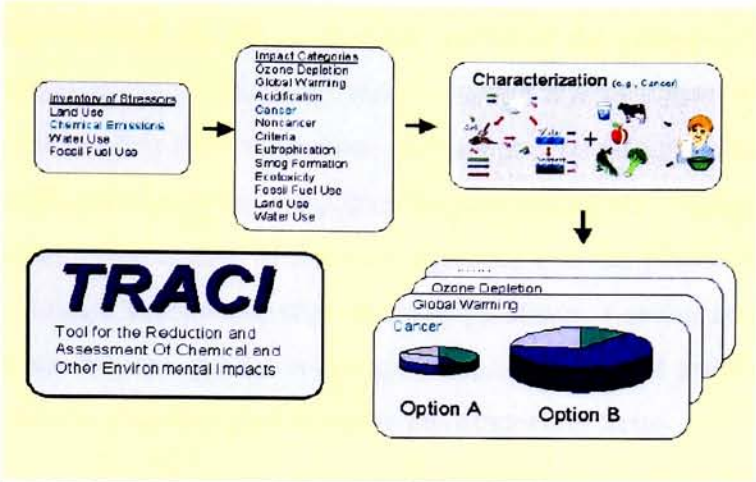


Fig 2.7 TRACI's Framework.

The Tool for the Reduction and Assessment and other Environmental Impacts (TRACI) was developed by the U.S. Environmental Protection Agency (EPA) under the direction of Jane Bare. Jane Bare is a chemical research engineer who works for EPA since 1985 addressing issues such as accidental chemical releases and impact assessments. Other research supporters for the creation of this software package were Teresa Hoagland, Patrick Hofstetter, and David Pennington. Other organizations such as ICF Consulting and Science Applications International corporation (SAIC) served as contractor support for TRACI development. ICF consulting efforts were led by Thomas Gloria while SAIC efforts were led by Alina Martin. Additionally, The University of California at Berkeley participated in the development of this project, under the direction of Tom McKone and Edgar Hertwich.

"TRACI allows the examination of the potential for impacts associated with fossil fuel and chemical releases resulting from the processes involved in manufacturing a product. TRACI allows the user to examine the potential for impacts for a single life cycle stage, or the whole life cycle and to compare the results among products or processes".
(Jane C. Bare, 2002).

A total of 11 categories are being evaluated, including ozone depletion, global warming, acidification, eutrophication, photochemical smog, eco-toxicity, human cancer, human non-cancer, human health criteria, fossil fuel depletion, and water use.

Two years later the EPA revised the software, and the environmental categories of land use and water use were not included in the new version of the software TRACI 1.1. EPA authorities explain that these categories were removed due to a lack of consensus and applicability in the context of comparative assessment. The collection and development of TRACI methodologies is an initiative that attempts to support a variety of constituent including industrial organizations, ecological agencies and the public in general, when performing their impact assessment of products or processes. Another attribute of TRACI is that the software has the ability to compare similar or related products/processes to determine and identify superior alternatives in environmental terms.

2.3.2 TRACI's Functions

TRACI provides the organization of the Life Cycle Inventory (LCI) in order to analyze the data entered and performs a Life Cycle Impact Assessment (LCIA). TRACI itself does not contain a pre-loaded life cycle inventory, meaning that the results obtained from the calculation phase are going to be dependent on the releases and resources previously entered. TRACI divides its impact categories into two major groups. The first group refers to the impact related to chemical releases while the second group addresses resource depletion. Nine of the TRACI categories are specific to chemical releases and the Fossil Fuel Use is the only category that measures the impact of resource depletion.

2.3.3 Midpoint Method

Many of the impact assessment methodologies within TRACI are based on "midpoint" characterization approaches (Bare et al. 2000). Of the nine TRACI categories related to chemical releases, eight are based on what is called midpoint level characterization, making an exemption for the impact of human health criteria. In the "midpoint approach" the first step is to identify the cause-effect chain of the impact category to be investigated.

Midpoint characterization means that the model used for TRACI to evaluate the categories does not include direct harm to an area of protection (AoP), known as an endpoint. For instance, Nitrogen is one of the chemicals that have the potential to affect the Eutrophication category, but it is not a direct measure of nitrogen's potential to cause direct harm to humans and animals.

2.3.4 Endpoint Method

In the category of Human Health Criteria, TRACI uses the endpoint as a point of reference to assess environmental impacts. This methodology is based on scientific evidence which proves that concentrations of air pollutants are related to changes in respiratory patterns and mortality rates. DALY is a combined measure of years lost because premature mortality and equivalent years lost because of 'lower quality of life' associated with health problems. One DALY represents the lost of one year of 'healthy life' The results characterized by the emissions of criteria pollutants are a measure of what is known as Disability-Adjusted Life Years (DALYs), which combines years of life lost and years lived with disability both standardized in terms of severity weights." For instance $P\mu_{10}$, have the impact factor of 0.083 DALYs/ tonne of emission.

Cause-effect chain selection

Impact Category	*Midpoint level selected*	*Level of site specified*	*Possible endpoints*
Ozone Depletion	Potential to destroy ozone based on chemical's reactivity and lifetime	Global	**Skin cancer, cataracts, material damage, immune-system suppression, crop damage, other plant and animal effects**
Global Warming	Potential global warming based on chemical's radiative forcing and lifetime	Global	**Malaria, coastal area damage, agricultural effects, forest damage, plant and animal effects**
Acidification	Potential to cause wet or dry acid deposition	US east or west of the Mississippi River, US census regions states	**Plant, animal, and ecosystem effects, damage to buildings**
Eutrophication	Potential to cause eutrophicacion	US east or West of the Mississippi River, US census regions, states	**Plant, animal, and ecosystem effects, odors and recreational effects, human health impacts**
Photochemical Smog	Potential to cause photochemical smog	US east or West of the Mississippi River, US census regions, states	**Human Mortality, asthma effects, plant effects**
Ecotoxicity	Potential of a chemical released into an evaluative environment to cause ecological harm	US	**Plant, animal and ecosystem effects**
HumanHealth Criteria	Exposure to elevated particulate matter less than 2.5 Mm	US east or West of the Mississippi River, US census regions, states	**Disability-adjusted life-years (DALYs), toxicological human health effects**
Human Health Cancer	Potential of a chemical released into an evaluative environment to cause human cancer effects	US	**Variety of specific human cancer effects**
Human Health Non-Cancer	Potential of a chemical released into an evaluative environment to cause human cancer effects	US	**Variety of specific human toxicological noncancer effects**
Fossil Fuel	Potential to lead to the reduction of the availability of low cost/energy fossil fuel supplies	Global	**Fossil fuel shortages leading to use of other energy sources, which may lead to other environmental or economic effects**
Water use	Not characterizes at this time		**Water shortages leading to agricultural, human, plant and animal effects.**

Table 2.2 Characterization of midpoint levels by TRACI environmental categories.(Bare et al. 2000)

The indicators and associated level of methodologies used in TRACI are illustrated in table 2.2

There are four steps that TRACI uses in order to complete an entire life cycle impact assessment, including:

1. Completing a project description form.
2. Creating a list of products to be analyzed.
3. Entering the life cycle inventory data for each product.
4. Generating the calculations.

Data in TRACI are organized hierarchically in the following sequence:

1. Project: Name of the project
2. Products: Names of the products and processes to be analyzed
3.Life Cycle Stages: Each one of the stages involved in the entire life cycle impact assessment of a product or a process. Life cycle stages are pre-defined as raw material acquisition, materials manufacture, product fabrication, filling/packaging/distribution, use/reuse/maintenance and recycle/waste management. These stages cannot be modified.
4. Processes: Each life cycle stages include one or more processes. Users can customize process names.

Regarding chemical releases, TRACI contains a list of chemicals ranging from those, which are commonly used in industry to relatively rare substances. It is not possible to add chemicals that are not on TRACI's list, as they will not be factored into the impact assessment. TRACI enables the user to assign a different geographic level for each process. Once a process location is selected, all resource usage and chemical releases for that process are assumed to occur in the selected location. If there is not a factor for a particular resource/release for the location specified TRACI would find the closest available geographic factor by impact category. The importance of this feature lies in the fact that TRACI will determine if there is a "region-level characterization factor" for each impact category. For those categories that do not include any region-specific characterization factors, general US values will be used. For the purpose of this study, no region-level characterization factors were include in the analysis.

One of the steps of the software is to select the "Scope" of the project from the drop down list: *cradle to grave, cradle to entry gate, entry gate to exit gate, or exit gate to grave.* These stages are explained below:

1) *Cradle to grave*: includes all product stages from raw to materials acquisition to waste disposal.
2) *Cradle to entry gate*: assesses just the upstream suppliers and transportation before the product reaches your company.
3) *Entry gate to exit gate*: assesses the product only during the time it is at your facility.
4) *Exit gate to grave:* analyzes the product from the time it leaves your facility to the time to the time at which it is disposed.

The next step is to enter the description of the project. This description should include any assumption related to the data used in the experiment when conducting the assessment.

2.3.5 TRACI Calculations

In order to have a better understanding of how the software tool performs the life cycle impact assessment it is necessary to review in detail each one of the methodologies used for each category. However, one common aspect of all the categories is that for each stressor (set of conditions that may lead to an environmental impact) a characterization factor is assigned with the objective of quantifying the magnitude of the potential impact of each inventory flow. In some situations one chemical may affect more than one category, and in those cases different characterization factors will be assigned depending on the categories being evaluated and the potential impact that the chemical represents for those categories.

After entering all the necessary data (inventory) into the software (definitions, statistics collected, technology, procedure, year of the data collection, stages) the next step is to run TRACI's calculations.

TRACI will start calculating the results and forming tables and graphs, always depending on the number of resources/releases being analyzed. There are three calculation types: *Inventory, Classification and Characterization.* The user may decide to sort the results by process, media, and quantity. The Inventory results contain all of the data entered or imported to TRACI. Therefore, this type of calculation can be used to compare the list of chemicals imported against your original spreadsheet and also to determine if any chemical were not imported. In effect, the *Inventory* calculation just reviews all the data you entered into the software.

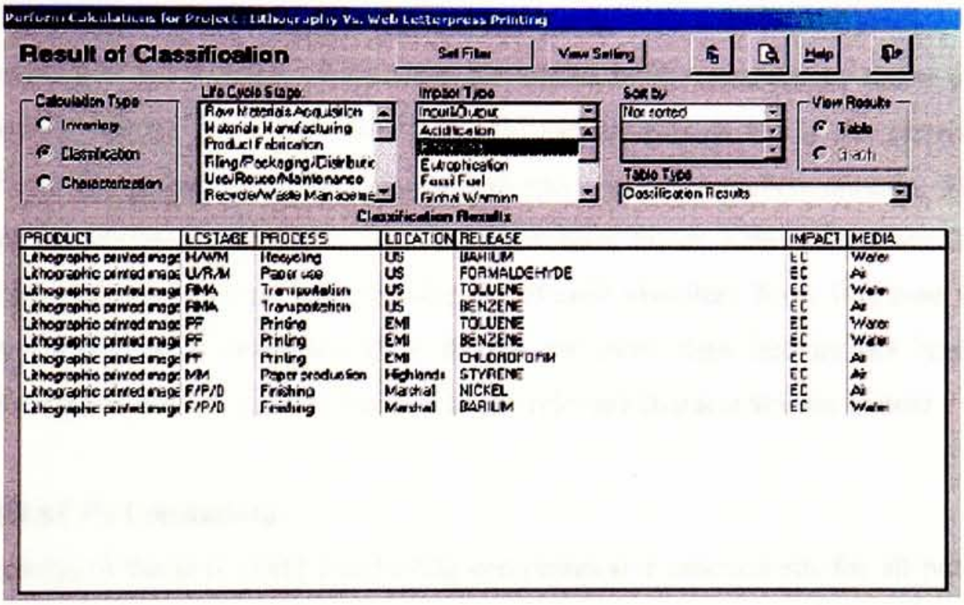


Fig 2.8 Classification results

In *classification* (Fig 2.8), TRACI assigns and aggregates results from the resource/releases inventory into environmental impact categories. Each resource/release is assigned to one or more of the impact categories based on the methodologies in TRACI.

The graphic below (Fig 2.9) shows an example of the characterization tables generated by the software calculations.

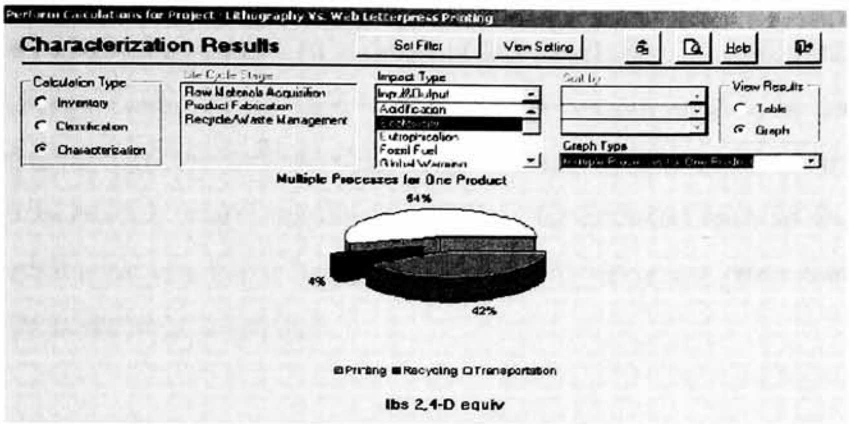


Fig 2.9 Characterization Results

TRACI multiplies the quantity of the resources/release by the equivalency factor for the corresponding impact categories. (For example, carbon dioxide has a characterization value of one for global warming. If your inventory includes carbon dioxide, TRACI multiplies the inputted quantity by the characterization factor. Characterization factors quantify the magnitude of the potential impacts of each inventory flow. In a case where chemical releases have characterization factors for more than one impact category, TRACI multiplies the full quantity by each of the relevant characterization factors.

2.3.5 TRACI's Limitations:

Unfortunately, in the real world completing comprehensive assessments for all potential effects of an entire product life-cycle would require large amounts of time, data, and resources. "Since every study is limited in resources, every study must also be limited in sophistication and/or comprehensiveness" (Bare 1999). Major limitations encountered in TRACI package are:

1. No life-cycle stages can be modified. No chemical can be added to TRACI database to maintain the integrity of the software.
2. TRACI does not provide estimates of actual risk. TRACI is simply a screening tool to allow consideration and quantification of the potential for impacts.
3. TRACI is not intended for studies of accidental situations (e.g., accidental oil spills).

4. TRACI focuses on normal industrial operations.
5. The most difficult limitation found in TRACI for the purposes of this study, was the fact that all energy requirements must be entered in terms of fossil fuels (coal, oil and natural gas). As a result of this restriction, the electricity and renewable energy consumption used for material processing need to be converted to fossil fuel energy and expressed in terms of those fuels. In order to do these energy conversions, many implications had to be included such as the energy content encountered in fossil fuels and also, the efficiency lost when transforming energy from one way to another.

2.4 TRACI ENVIRONMENTAL CATEGORIES

2.4.1 Ozone Depletion

Ozone is an unstable form of molecular oxygen containing three atoms (O_3). These oxygen molecules break apart when they receive radiation from the sun, forming new chemical compounds and hazardous reactions for the earth's surface. O_3 is considered to be an air pollutant in most industrialize countries because at high concentrations is known to reduce human lung capacity as well as to damage the cells of many plants, animals and living organisms. On the other hand, ozone is necessary in the stratosphere, because it serves as a protective layer that obstructs solar ultraviolet rays (UV) of reaching the troposphere where people live and breathe. The destruction of the ozone layer which protects all living things from harmful solar radiation, was one of the first general environmental problems know by society.

In simple terms "Ozone Depletion" is the reduction of the protective ozone in the stratosphere aggravated by emissions of ozone–depleting substances. Humans have been damaging the ozone layer by releasing molecules such as chlorofluorocarbons (CFCs). These types of molecules are commonly applied in the manufacturing sector when fabricating aerosols products, but when released to the atmosphere they become unstable, allowing the penetration of solar rays over the earth's surface. Once UV rays impact these molecules, they break down, releasing atomic chlorine and bromine that provoke ozone destruction.

According to statistics reported by the Union of Concerned Scientists, for every three millions molecules of air, two millions are breathable O2, and only three are Ozone. Yet this small amount of ozone is enough to prevent most particular ultraviolet-B (UV-B) radiation from reaching the earth surface. The damages of these UV-B light rays may penetrate deep into water and skin, being even capable of affecting genetic material. The increase in UV-B radiation associated with ozone depletion increases the severity and the variety of short-term and long-term health effects. The real concern about this UV-Bs is that its radiation may lead to problems such as skin cancer, eye damage and possible inhibition of immune systems functions in humans and animals. Besides, these rays have adverse effects on the plants, affecting process such as photosynthesis, and the protein and pigment content of some plants. Zooplankton and other aquatic communities of amphibians are very sensitive to UV-B.

The largest ozone depletion know to date occurred over the Antarctica range between 13 and 21 km, measuring 8.2 million square miles-larger than the United States and Canada combined- and the problem is not limited to Antarctica. The Atmospheric Science Panel predicts that the ozone layer will be in its most vulnerable state during the next two decades and some of the effects are expected to occur through the next century. The challenge that the scientist and the humanity have to face is big. The main step is to gain a genuine understanding about how this ecological problem can be minimized and at the same time how the depletion process can be controlled.

The equivalency potential factor for Ozone Depletion category is **CFC-11 equivalents/kg of emission.**

2.4.2 Acidification

Pollutants in the air can generate acid rain, smog, and at the same time, they can cause respiratory problems and other grave health illnesses. Substances such as sulphur dioxide (SO_2), nitrogen oxides (NO_x) and ammonia can provoke a harmful process called acidification. Sulphur makes the biggest contribution to this environmental problem.

In the acidification process, SO_2 and NO_x emitted into the atmosphere can be oxidized into sulphur acid and nitric acid, causing acid rain. Acid rain can affect soil, vegetation and water. Waters can become acidified naturally over long period of time, but ecological studies have shown the magnitude of acidification during the last 150 years to be considered greater than in the last 1000 years, due to the increase of sulphur and nitrogen compounds into the atmosphere. Acidification problems became evident in the 1960s, and the threat of "acid rain" was very serious, with fish disappearing from some lakes.

Acidification occurs when the capacity of the soil and water bodies to resist or neutralize acidifying atmospheric deposition begins to decline. These compounds may fall to the ground with rain or snow as wet deposition or in the form of particles or gases as dry deposition. Rainfall is naturally to some extent acidic, but several air pollutants can increase the acidity level notably. The Acidification process also releases metals that can damage the microorganisms in the soil that are responsible for mud decomposition. Corrosion also constitutes another consequence of the acidification effects, greatly accelerated by SO_2 and NO_x when these are transformed into strong acids that attack buildings, monuments and historical aircrafts.

The Kyoto Protocol under the framework convention of climate change, proposed that countries takes a serious commitments to limit emissions of the greenhouse gases, by improving emission control technologies, switching from coal and oil to natural gas and using energy in a more efficient way. The objective is to reduce acidifying emissions, and indeed, in countries such as Europe sulphur emissions have started to fall. Due to legislation and several controls implanted in the European Union such as the "Sulphur Protocol", sulphur emissions have been reduced by 44 % in the period 1990-1998. Simultaneously, emissions of nitrogen oxides fell by 21% over the same period while ammonia fell by around 15%. But there is still much to do in order to reach environmental targets to control this ecological problem.

In TRACI the characterization factors for this category are expressed (hydrogen ion concentration of water and soil systems) in **H+ mole equivalent deposition/ kilogram of emission** of the chemical affecting this environmental category.

2.4.3 Eutrophication

"Eutrophication is the most common impairment of surface waters in the U.S, responsible for about half of the impaired lake area and 60% impaired river" (Carpenter at al. 1998). Eutrophication is the process by which water becomes enriched with plant nutrients- most commonly phosphorus and nitrogen- thereby causing excessive growth of aquatic plants. Normally, this process takes thousand of years to progress, but similar to other environmental problems; human activities have accelerated this process in thousands of lakes around the world.

The real concerns related to Eutrophication is that it promotes algae growth and when plants dies can lead to oxygen depletion, affecting the quality of the water (low in oxygen content), fishes and other aquatic organisms. Fish for example, can be asphyxiated by very low oxygen concentrations in the water; thus, blue-green algae can produce toxins, poisoning freshwater reservoir supplies. During 1960s, Lake Erie was undergoing rapid Eutrophication, becoming a point of attention for many ecological institutions. This process is also called "water pollution" and "nutrient pollution" because in the past decades humans have added excessive amount of plant nutrients to the lakes in several ways, including the disposal of contaminated water that contains phosphate, which has been proved to be stimulant of algae production.

Interestingly, by using small lakes as experimental scenarios, scientist at the Experimental Lakes Area (ELA) were able to add various combinations of nutrients with the objective to determine which of the major plants nutrients –carbon, nitrogen, phosphorus- was the key for controlling Eutrophication in lakes.

In this experiment seven different ELA lakes were fertilized in various ways and two of them were particularly important in demonstrating that phosphorus was the key nutrient for the control of the phenomenon in discussion.

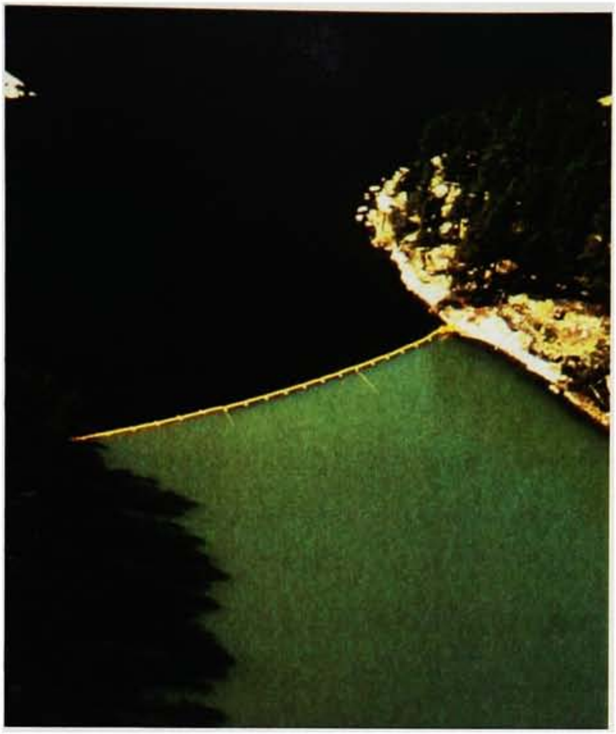


Figure 2.10- View from above ELA Lake divided by a curtain in August 1973.
(Source: Experimental Lakes Area, 1973)

The lake showed in the graphic above (fig 2.10) was a site of a visually spectacular experiment. The lake was divided into two equal portions. Carbon and nitrogen were added to one half of the lake, while carbon, nitrogen and phosphorus were added to the other half. After 8 years the half receiving phosphorous developed algae while the other side receiving only carbon and nitrogen did not, convincing all the researchers that phosphorus is the key nutrient. The bright color results from blue green algae, which reflect the side where phosphorus was added as part of the experiment. Some states are taking action concerning the Eutrophication problem. Nutrient reduction targets are allocated among Maryland, Virginia, Pennsylvania and the District of Columbia.

The TRACI characterization factors for Eutrophication estimate the potential of chemical release containing **Nitrogen (N) or Phosphorus (P) to air or water/ kilogram of chemical released.**

2.4.4 Global Warming

Global warming is the gradual increment in global temperatures caused by the emission of gasses that trap the sun's heat in the Earth's atmosphere. Gases that contribute to Global Warming include carbon dioxide, methane, nitrous oxide, chlorofluorocarbons (CFCs) and perfluorocarbons (PFCs) etc. The U.S. Greenhouse Gas Emissions report 1990-2000" reports that changes related to the atmospheric concentrations of these greenhouse gasses can alter the balance of energy transfers between the atmosphere, space, land and oceans. Each greenhouse gas differs in its ability to absorb heat in the atmosphere. For instance, methane absorbs 21 times more heat per molecule than carbon dioxide.

Scientists generally agree that the Earth's surface has warmed by about 1 degree Fahrenheit in the past 140 years, concluding that warming in the 20th century is greater than at any time during the past 400-600 years. According to the Union of Concerned Statistics, seven of the ten warmest years in the 20th century occurred in the 1990s. In addition, The National Academic of Sciences in Washington DC- based on the hypothesis that concentrations of greenhouse gasses will increase and accelerate, and making assumptions about how the climate will react to that- by computer modeling they suggest that average Earth surface temperatures will rise between 2.5 and 10.4 degrees Fahrenheit by the end of this century.

Changing climate conditions may affect human health, animals and many types of ecosystems. There are a growing number of studies showing that plants and animals change their behavior in response to shifts in climate. For example, early arrival of migratory birds has been linked with this ecological situation. Global warming is causing serious disruptions to our environment and lives. Some of the harmful consequences of this phenomenon are a faster rise in a sea level, detrimental water events that produce floods and property destruction and a great potential of heat-related illnesses. According to the Environmental Protection Agency (EPA), most of the United States is expected to warm, but currently, scientists are unable to determine which parts of the United States will become wetter or drier.

Actions to mitigate and slow the pace of Global Warming can still be taken. Since this ecological problem primarily is a result from human activities involving the burning of fossil fuels, some policies and strategies- such as better technologies- can be implemented in order to reduce the amount of emissions wherever possible. The TRACI unit for Global warming is **CO2 equivalents/kg of emission**

2.4.5 Photochemical Smog

Photochemical Smog is defined as type of air pollution caused by chemical reactions among various substances and pollutants in the atmosphere. It is a mixture of pollutants that is formed when nitrogen oxides and volatile organic compounds (VOCs) react to sunlight, creating a brown haze above cities. It tends to occur more often in summer, because that is when we have the most sunlight, causing poor visibility, eye irritation and damage to material and vegetation if sufficiently concentrated. Also, photochemical smog is characterized by the presence of irritating substances in the atmosphere and two of the most important of these are ozone and peroxyacetyl nitrate (PAN). Both compounds are highly toxic to plants and people.

Photochemical reactions take place mostly in cities where there are many cars and trucks. To have an idea about how the reaction happens, the photochemical smog formation goes according to the following scheme. First, hydrocarbons are unburned fuels resulting from incomplete combustion, while nitrogen oxides are formed in small amounts when air is heated to a high temperature, the same as occurs during car combustion. Nitrogen oxide is brown and its causes the dark color of the smog, and absorbs the sunlight. This reaction leads to the ozone formation, which is one of the major components of the smog. Hence, the ozone absorbs ultraviolet light and a chemical called hydroxyl is formed. In small proportion the hydroxyl is converted into a toxic PAN, and this can stay in the atmosphere for a long time. Also called "Sunlight-driven" this type of pollution has been most studied in Los Angeles (USA) where it has been an environmental problem for at least forty years. Several researchers have shown conclusively that car combustion is a primary contributor to the photochemical smog formation.

Consequently, California was the leader in creating programs and laws concerning the control of car emissions for the reason that Photochemical Smog can have detrimental effects on the environment and on people's health. The chemicals involved in the formation of this kind of air pollution can have harmful effect on plants, reducing the photosynthesis process and stopping the growth in flora. However, the biggest concern is about the negative effects encountered on people's health.

Pollutant	**Effects**
Nitrogen Oxides	▪ can contribute to problems with heart and lungs ▪ links to decreased resistance to infection
Volatile Organic Compounds (VOCs)	▪ eye irritation ▪ respiratory problems
Ozone	▪ coughing and wheezing ▪ eye irritation ▪ respiratory problems
Peroxycetyl Nitrate (PAN)	▪ eye irritation ▪ respiratory problems

Table 2.3 Health effects of pollutants involved in Photochemical Smog

Table is 2.3 describes how these pollutants may affect the health criteria on humans. Other type of air pollution called "Industrial Smog" can be extremely toxic to humans and other living organisms. One of the most famous events related to industrial Smog occurred in London in December 1952, when five days of calm foggy weather created a toxic atmosphere that cost about 4000 human lives. An aggravator to this incident was that since London is known for its fog, there was no great panic among people and only weeks after the event people did realize the magnitude of this happening.

The most effective way of reducing the of occurrence of photochemical smog is to control the emissions of the primary pollutants: NO and VOCs in the troposphere. The implementation of emission control in car's engines are actually being developed by manufacturers. But most important, this problem requires cooperation among government, industries and individuals.

TRACI incorporates the following components to evaluate the smog characterization factors: 1) the influence of individual VOCs on smog formation, 2) the relative influence of NOx concentrations versus average VOC mixture of smog formation, 3) impact of emissions upon concentrations by state and release location. The TRACI units for this category is **MJ surplus energy /MJ of extracted energy.**

2.4.6 Fossil Fuel

Fossil Fuels are energy resources that come from the remains of plants and animals. These days, because of the advances that humanity has reached in technology, we can retrieve these fossils fuel from the ground and under the sea and have them converted into electricity. As a result, it is estimated that 90% of the world's electricity demand is generated from the use of fossil fuels, representing the humanity's most important source of energy. Coal is primarily used to produce electricity; oil is responsible for our transportation system, giving us the mobility in our cars, planes, trucks, boats; and natural gas is used to produce heat, hot water, and industrial processes.

Coal is our most abundant fossil fuel resource. It is a complex mixture of organic chemical substances containing carbon, hydrogen and oxygen; all this together with small concentrations of nitrogen and sulfur. Crude oil consists of a mixture of hydrocarbons with variations in the molecular weight, presenting dissimilarities from one molecule to the other in structure and properties. Oil has a variety of properties; some forms are black, others dark green, and some light. The liquid content may range from very viscous to easy flowing. The last fossil fuel is natural gas, which is a highly flammable hydrocarbon gas consisting of methane (CH4). Although methane is the main component, it may also include other gases such as oxygen, ethane, hydrogen, nitrogen, ethylene, propane, etc. As a fuel, is convenient and efficient, being use primarily for heat in industries and residencies because has the great advantage of producing no smoke, ash or burning. The only weak point about this type of fuel is that usually is much more expensive than coal and oil.

The major limitation that fossil fuels present is that unfortunately, they are not considered a renewable energy source and aside from the environmental impact, the cost of retrieving and converting them is becoming extremely high. They take million of years to develop under extreme conditions. Fossil fuels downfall is the impact they have on the environment. The burning of fossil fuels is responsible for emissions that contribute to major ecological problems, such as global warming, ozone depletion and acid rain. Combustion of these fuels is considered to be the largest contributing factor to the release of greenhouse gasses into the atmosphere. For that reason, it is believed that energy providers are the largest source of atmospheric pollution today, because all the harmful outcomes resulting from the process of converting fossil fuel to energy. Some of these outcomes include air pollution, water pollution, the land degradation and human diseases. In addition, converting fossil fuels may result in the accumulation of solid waste, requiring a huge amount of land space and demanding the appropriate monitoring for toxic waste. These kinds of toxic wastes can endanger surrounding vegetation and marine life. Also, oils spills can result in a big disaster when transporting fossil fuel, causing vast damages and destruction for aquatic life.

The TRACI units for this category is **g of Nox equivalent/kg of emission**

2.4.7 & 2.4.8 Human Health Cancer and Human Health Non-Cancer Effects

Cancer is defined as a general term for more than 100 diseases characterized by abnormal and uncontrolled growth of cells. The resulting mass- called tumor- can invade and destroy surrounding normal tissues. Unfortunately, cancer cells from tumors can spread to the bloodstream system to start new cancers in other parts of the body and because cancer cells continue to grow and divide, they are different from normal cells; instead of dying, they live longer than normal cells and continue to form new abnormal cells.

Chemicals emissions that may cause cancer in humans are known as "carcinogens". The International Agency for Research On Cancer (IARC) defines carcinogens as "potential cancer causing-agents in the environment." In the last 20 years, Benzene has been shown to be a carcinogen related to leukemia, lymphomas and other types of cancers.

Other chemicals such as hydrocarbons, asbestos, and hexavalent chromium have been shown to be carcinogenic. (IARC) has identify fifty-nine agents recognized as being irrevocably linked to human cancers, including cadmium (lung cancer), lead, lead compounds, and ethylene. In the process used by EPA to determine the potential health effect in humans associated with exposure to chemicals, non-cancer effects are also evaluated. One of the chemicals more related to non-cancer health effects is polychlorinated biphenyls (PCBs) group of compounds mainly used in the electricity supply industry and mining- having very serious potential implications for the health of humans and animals. Also, other non-cancer effects of PCBs that have been encountered in animals and humans include dermal and ocular health problems. Added to the list, other health concerns are elevations in blood pressure, serum cholesterol, and effects on the immune systems that may have significant implications in the human organism. (EPA, 2004).

There is much controversy about certain chemicals that may cause cancer in animals because the potential for those chemicals to provoke cancer on humans are either unknown or unproved. However, EPA evaluates the ability of a chemical to cause cancer based on a weight of evidence of human epidemiological and animal toxicity studies; meaning that the experiments with animals at certain point are considered valuable information to make appropriate conclusions about chemicals and their potential to cause cancer in humans. EPA also develops risk factors that indicate the relative potency of any chemical (the ability of a given dose to cause cancer).

The toxicological content of an emission for human health is currently calculated in TRACI based on human toxicity potentials (HTPs). Distinct HTPs are calculated for each exposure pathway, release medium (currently emissions to air and water) and type of effect (carcinogenic or non-carcinogenic). Also, values of the calculated non-cancer and cancer HTPs are reported for each release medium. The HTPs for each chemical are compared to baseline values using benzene for carcinogens and toluene for non-carcinogens; therefore, chemicals are comparable in terms of toxicological equivalencies.

The specific TRACI unit for these categories is **Benzene equivalents/kg emission** and **Toluene equivalents/kilogram** of emission for Human Cancer and Human non-Cancer respectively.

2.4.9 Human Health Criteria

This category reflects the adverse consequences that chemicals and air pollutants my have on human health. These chemical concentrations on the environment are associated with changes in respiratory patterns and also with changes in mortality rates. Particulate matters such as PM less than 10 mm in diameter ($P\mu_{10}$), PM less than 2.5 in diameter ($P\mu_{2.5}$) and emissions of SO_2 and NO_x, are the chemical emissions considered to evaluate the human health impacts on this category. In order to determine the emission and exposures Nishioka (2000), used what is called "intake fraction" that in simple terms is the fraction of a pollutant emitted that is actually inhaled, representing which are the probability for an emitted molecule of emission to be inhaled.

An important concept considered in this category is "Burden of Disease" developed by Murray and Lopez (1999) used to estimate the health loss associated with air pollution. Also, environmental disease-related disability weights have been provided by De Hollander (1999) using the "Global Burden of Disease" and the "Dutch Burden of Disease" projected to attribute weight to environmental impacts. The potential effects of criteria pollutants are matched with the DALY methodology which exists for respiratory effects and mortality effects. DALY measures combined years of life lost and years lived with disabilities that are standardized by means of severity weights.

The TRACI units for this category is **DALYs/tonne emissions**

2.4.10 Eco-toxicity

Eco-toxicology is the study of how chemicals affect the environment and the organism living on the earth. Hence, if a chemical affects one organism in the ecosystem, other organisms at the same time will be affected, since all living beings depend on one another. The objective of this field is to identify the concentration of chemical at which an organism will be affected, in order to avoid getting to that point to protect the environment. Ecotoxicity measures toxic effects on soil, water, flora and fauna.

In TRACI, the ecological toxicity potential (ETP) is a quantitative measure to express the potential ecological harm of a unit quantity of chemical released to the environment. The objective of the ETP is to establish a rank measure of potential ecosystem harm for a large set of toxics coming from industrial and agricultural chemicals. Thus, the ETP is designed to captured the direct impacts of chemicals emission from industrial systems on the health of plant and animal species. The ETP set includes 161 chemicals, for emission to air and surface water.

An ETP is calculated based on potential terrestrial and aquatic ecosystems impacts. In TRACI **2,4-Dichlorophenoxyacetic acid (2,4-D) is used as a reference substance.**

2.4.11 Water User

Water is one of the most critical natural resources and although water covers more than two-thirds of the Earth's surface, fresh water represents less than 0.5% of the total water on the Earth. An enormous amount of water is being wasted in industry, agriculture and urban areas, but technology can play an important role optimizing the way in which humans are utilizing water resources. Certainly, human population have increased, provoking the contamination of water. One of the major concerns of the environmental organizations and the public in general is the magnitude of the contamination of the water as a result of industrial activities. Many chemicals and toxic substances enter rivers, oceans, and lakes, getting dissolved or suspended in water. These practices conclude in water pollution, deteriorating the quality of the water and affecting aquatic ecosystems.

The major source of water pollution comes from industrial effluents and chemical discharges. Yet heavy metals called Persistent Organic Pollutants (POPs) is a new type of contamination affecting water quality and causing health impacts.

Biochemical Oxygen Demand (BOD) is the amount of oxygen required by microorganism to decompose the organic substances in sewage. As a result, if there is more organic material to decompose, more BODs is needed for this aquatic organism to make their job. Thus, the oxygen dissolved in water determines the quality of the water, to the point that when the dissolved oxygen drops their normal level, many aquatic species die. If the oxygen levels drops to zero, the water will become septic. Polluted water is not only devastating to aquatic animals, but to people, birds and all living organisms.

In TRACI, rather than attempting to measure the amount of pollutants into the water and their effect on the environment, for this category, the LCA software is structured to capture the amount of water use in areas suffering from low water accessibility. There is not a clear methodology used to perform the impact assessment for this category.

3. LITERATURE REVIEW

In order to measure the different benefits of remanufacturing as a production strategy, many researchers have conducted different studies using a series of qualitative and quantitative engineering tools. The performance of most remanufacturing processes depend on several aspects of the system requirements. Therefore it is essential to look at the entire product/system life cycle when assessing the benefits of the remanufacturing industry. Most research to date has focused on applying technical strategies, where life cycle assessment (LCA) forms part of this list. Unfortunately, few studies have attempted to quantify the environmental benefits of remanufacturing taking into account the entire life cycle of a process/product.

2.2 Remanufacturing literature

Throughout the last two decades many authors have conducted research on remanufacturing. Those studies have addressed a variety of problems encountered in the typical remanufacturing environment. Particularly, significant attention has been given to issues such as disassembly techniques, reverse logistics, balance between returns as well as time and quantity uncertainty for returns. Along the same lines, processing time, design for disassembly; design for remanufacturing, and remanufacturing technology include several implications that increase the difficulty of management and planning operations within this industry.

Robert Lund has been studying the remanufacturing industry since 1978, first at Massachusetts Institute of Technology and later at Boston University. His research emphasizes the growth of the remanufacturing industry over the last 25 years. One of the most important findings in this study was the identification of 83 product areas that are routinely remanufactured. Muckstad and Isaac (1981) proposed one of the first production planning models for demands and returns. Afterwards, in (1983), Lund began compiling general research on remanufacturing. Since remanufacturing is considered an industrial process to restore worn-out products into like-new ones, disassembly has been a major element of discussion among different authors.

Cleg and Williams (1994) analyzed how disassembly was being performed in most of the industries, concluding that manual disassembly systems predominate within this environment and also stating that automated disassembly systems will be feasible only when working with high volumes of products. Brennan (1994) identified various technical and operational challenges in the area of disassembly, including in his study an extensive investigation about reverse logistics and disassembly scheduling. A great contribution to the field was done by Gupta (1994) who developed a reverse logic material requirement planning (MRP) algorithm for use in planning disassembly. This algorithm attempted to control: 1) the accumulation of material, 2) the related problems with inventory control and 3) the increased complexity in scheduling and resource allocation.

Flapper (1995) pointed out the need for a systematic method to control and plan operational activities concerning product reuse. Johnson and Wang (1995) worked in the design of a four-level approach to the disassembly problem for material recovery. Knowing that an optimal solution to the recovery problem seeks to balance the cost of disassembly with the revenue from material recovery, their goal was to maximize revenue by adopting the optimal disassembly sequence, developing different optimization methods for material recovery. Thierry (1995) introduced what is defined as "take back" schemes, where his research examines the operations of a number of firms involved in recovery management and product reuse. Penev and Ron (1996) conducted a project in which a disassembly sequence was developed to recover value from products, in order to avoid increasing disposal costs.

Ferrer (1997) studied remanufacturing from the economic point of view, considering the value of recoverable parts and market specifications. Most of his studies are focused on determining the feasibility of remanufacturing for specific products; e.g. tires and personal computers. In those studies he proposed methods to manage a large volume of tires, including new and retired tires. That paper also discussed characteristics inherent to material fatigue and recovery yields.

In his analysis The impact of remanufacturing in the economy co-authored by Ayres, they described an input-output methodology as an instrument to evaluate the impact of remanufactured products on the present economy, applying the model to 30 industrial sectors of the French economy. Ayres (1997) suggested that remanufacturing is one approach to deal with used durable goods at the time of disposal because remanufacturing reduces the demand for raw material and at the same time provides an alternative to reduce the amount of products discarded in land fills.

In (1998), Lund released his work Hidden Giant as the first attempt to define the size and scope of the US remanufacturing industry. The 2-½ year study gathered confidential information from hundreds of industries. The evaluation of this data constitutes a comprehensive approach to how the industry is restoring life to a wide variety of products, where the automotive sector represents the largest segment (57%) of the remanufacturing industry. The following chart (Table 3.1) provides details for 83 products that are being constantly remanufactured in the US.

Sector	Product Areas
Automotive & Other Transport	12
Compressors	2
Electrical Apparatus	14
Machinery	42
Office Furniture	1
Tire	1
Toner Cartridges	2
Valves	1
Other	8

Table 3.1 Remanufacturing Product Areas- (Lund, 1996)

According to the article Assessment of remanufacturing technology, Dr. Nasr (1998), from the National Center for Remanufacturing and Resource Recovery (NCR^3) in Rochester, NY, reported that the vast majority- (85%)- of remanufacturing firms uses conventional equipment to process materials.

He explained that less than one quarter of facilities reported using computerized numerical control (CNC) machines, and a small percentage (approximately 6%) reported using manufacturing cells. Nasr also found that many remanufacturing firms used relatively simple production methods, e.g., job sequencing, and he remarked that almost all firms had very high labor content in their operations. In the same document, he indicated that few firms use any technical tools for formal decision making in disassembly and replacement. Den Hond (1998) reported that eight major automobile manufacturing companies in Europe established pilot disassembly and recycling facilities to learn efficient ways of dealing with end of life cycle vehicles.

Guide and Jayaraman (1999) authored a paper that discussed the production planning and control needs for a remanufacturing firm, presenting specific factors that complicate those operational activities. The study explored factors that impact production planning and control for a closed-loop supply chain to incorporate product recovery. Three case studies were illustrated, indicating the common activities required for all remanufacturing operations. After analyzing three different types of products, Kodak single use-camera, Xerox's photocopier, and US naval aviation aircraft, it was concluded that production planning and control for remanufacturing depends on product volume and the nature of process because each remanufacturing environment possesses unique complexity and has to face its own challenges.

A perfect part correlation between demands and returns does not often apply in a remanufacturing environment. Consequently, Van der Laan (1997) developed several models meeting different *PUSH* and *PULL* assumptions, where the two main parameters considered were the correlation between the return of used cores and the demand for remanufactured goods. Moreover, remanufacturing lead-time was one of the implications analyzed in this paper. In (1999), Van der Laan discussed a series of options for independent demand inventory control models using automotive parts and photocopiers as product examples.

The work presented by Kerr and Ryan (2000) Eco-efficiency gains for remanufacturing; A case study of photocopier remanufacturing at Fuji Xerox in Australia analyzed a well-established remanufacturing system by following the life cycle of a Xerox photocopier. In this study the objective was to provide a rigorous assessment of the contribution of remanufacturing in order to reduce total resource consumption and waste generation. The study was based on a comparison of the life cycles of remanufactured and non-remanufactured photocopiers in Australia. An analysis of the results showed that remanufacturing could reduce resource consumption and waste generation over the life cycle of the photocopiers used for this study. In addition, the paper described how remanufacturing can contribute more to sustainable product systems. However, this contribution will be limited by many aspects interfering with the production systems, such as product returns, product design, demand for remanufactured products, and the cost of remanufacturing relative to the cost of other production alternatives.

Research has been conducted on the various aspects of production planning and control in a remanufacturing environment, as well as economic benefits from remanufacturing. However, remanufacturing implications associated with environmental impacts has not been researched adequately. Practical research and experiments that connect the remanufacturing industry and its contribution to the environment as a solution to global ecological problems are still needed.

3.2 Life Cycle Assessment literature

First's research investigating the LCA approach started in the 1970s. These studies emerged in response to increased environmental awareness from government, industry, and the public in general. In the early stages, LCA focused on the evaluation of products, but LCA applications have expanded to examine production systems and to compare industrial activities. The LCA has been used for both corporate and public decision-making. Some of the more recent examples of LCA applications in corporate decision making include energy, transportation, chemical, nuclear, metallurgy, polymer, paper and forestry, textile, and electronic industries.

White et al (1995) conducted a Life Cycle Inventory (LCI) of Municipal Solid Waste (MSW), including relevant data for collection, biological treatment and residual waste disposal. Paper, garden, and organics materials constituted major components of MSW.

Donaldson (1996), conducted a LCA for the telecommunication, semiconductor and laser industries. Terho (1996), used LCA for the telecommunication cables industry. Van Mier et al., (1996) discussed the application of LCA for a Philips-branded monitor. Graedel and Allenby in 1996 developed an environmentally responsible assessment matrix to simplify the process of LCA and also reduce the amount of statistical analysis involved in those types of assessments. Azapagic (1999) discussed LCA application in process selection and design. A number of attempts have been made to incorporate LCA in public decision-making, e.g. EU eco-labeling schemes, packaging and packaging waste, and policies related to taxes on pollution. One such example is France, which introduced taxes on CO2 emissions based on LCA results. In addition, US EPA is encouraging the use of LCA in decision making for environmental problems affecting society caused by industry.

Given that product competition is a major concern among similar industries, several qualitative and/or quantitative methods have been proposed to simplify and reduce the amount of resources required to perform a product LCA. Computer modeling is an approach that complements the traditional full LCA, and should not be used to replace it, but to improve it.

Computer-aided LCA modeling methodology categorizes and quantifies the environmental attributes of a certain product within its life cycle into major impact groups, such as ozone depletion, greenhouse-gas emission, and acid rain. Parameters and indicators are defined to represent the different attributes.

The LCA methodology consists of inventory analysis, impact analysis, and interpretation. It is not straightforward and requires a large amount of data. Frequently, a good practitioner's experience is needed to conduct the experiment, or in the best case, professional service is recommended to perform a reliable LCA study.

Extensive studies concerning product LCA are available. A wide range of product evaluations has been performed in the past, for companies, government and environmental institutions. However, more investigation and research on conducting LCA for remanufacturable products and for remanufacturing system's performance is necessary. There is a need for detailed evaluation of potential eco-benefits and environmental savings that might be expected from the remanufacturing industry.

3.2.1 LCA Software

There are numerous environmental software tools available on the market for product design and LCA. These tools can incorporate large databases of environment profiles of materials, energy and fuel resources.

One of the most used worldwide LCA software tools is *ECO IT*, which calculates the environmental load and shows which parts of the product create the most damage. Also, ECO-IT has the capability of determining in which of the LCA stages the product may represent more potential damage for the environment. Based on this information it is possible to find out the best possible way to reduce the environmental load of the products.

ECO-IT uses an ECO-indicator score to express the environmental performance of a product as a single figure. These scores are computed following the Eco-indicator methodology, which is based on the principles of LCA impact assessment.

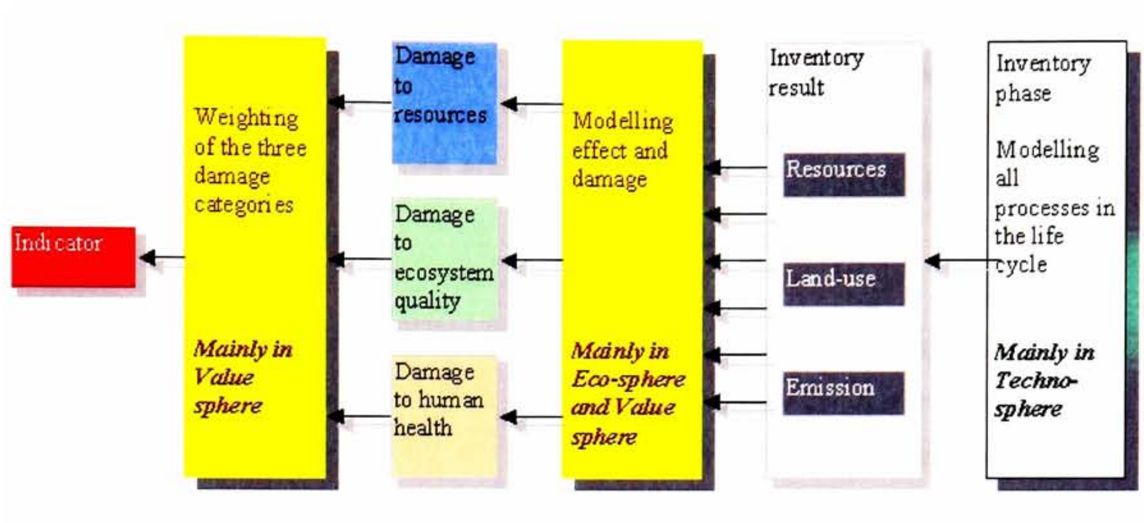


Fig 3.1 Eco-It indicator Methodology (Source: http://www.pre.nl/eco-it/default.htm)

Figure 3.1 shows an illustration about the methodology used by ECO-IT software to quantify the environmental load caused by product manufacturing. ECO-IT comes with over 200 Eco-indicators, using 99 scores for commonly used materials such as metals, plastics, paper board and glass, as well as production, transport, energy, and waste treatment processes. These indicators can be used like predefined building blocks to model the life cycle of products

In the same context, SIMAPRO 5.1 represents another LCA software tool commonly used for companies and universities worldwide. It was first released in 1990 and it uses the Eco-it indicator to analyze different scenarios. The software can be run in various languages such as English, Italian, French, German, etc. It contains several impact assessment methods and several inventory databases, which can be edited and expanded without limitation. It can compare and analyze complex products with complex life cycles.

A summary of others LCA tools is presented in table 3.2

Tool	Examples	Comments
LCA modeling tools	-SimaPro -TEAM -Gabi -Umberto -PEMS -Boustead	These tools come with detailed databases from many sources and also allow users to input their own unit process data. They are excellent analytical tools and generally have a range of impact assessment models. The data is mostly European origin.
Product assessment models	-EcoIt -Ecoscan -Idemat	These models draw on detailed data, but generally do not allow the user to specify new inventories. They focus on the product design and represent environmental impacts with a simple eco-point score.
Process assessment model	-P2Edge	These models use data and process information to alert the user to cleaner production and to design improvement opportunities.

Table 3.2 Life cycle assessment software tools (Source: Design + Environment, Lewis & Gertsakis)

As explained in table 3.2, different kinds of LCA software tools are actually used depending on the nature of the analysis that is being conducted and the type of industry performing the study. More LCA packages are offered in today's market to meet different needs and also to evaluate a variety of different environmental categories.

4- RESEARCH METHODOLOGY

4.1 Overview of the Study

The objectives of this research include identifying the resources and releases associated with the production process of aluminum, steel, and polyvinyl chloride (PVC) materials, which are the main components of the product to be evaluated in this study. After collecting the necessary set of data for these resources and releases, an energy consumption analysis was developed for all stages of the material's life cycle. Carbon dioxide emissions associated with those energy requirements were estimated. Other chemical releases- NOx, SOx, VOC, PM10- were documented and included in this LCI. The data collected was used to conduct a LCA for the selected product, an automotive water pump, which contains the three different materials mentioned above. The purpose of creating this LCI and conducting a LCA is to characterize resource consumption and environmental impacts associated with materials manufacturing. Another objective is to identify which processes contribute the most to resource depletion. Using the comprehensive data set gathered through this research, a case study is explored to understand whether or not remanufacturing represents a better production strategy to increase the number of product life cycles of a given product. Also, it is intended to determine if remanufacturing represents a practical alternative for product disposal.

4.2 METHODOLOGY

LCA is the methodology used in this study to understand the environmental effects arising from production systems. The first step toward performing this evaluation is to analyze, in detail, all the production implications- energy requirements, chemical releases, and water use- involved in the manufacturing process of each one of these materials. Subsequently, all production factors encountered in the remanufacturing system and in the typical manufacturing system are compared to conclude which production choice involve more gains, in environmental terms.

The scenarios to be evaluated are: 1) a life cycle assessment of a process/product using the stages of the traditional LCA model including: *raw material acquisition, manufacturing, use/reuse/maintenance, recycle/waste management,* and 2) a life cycle assessment including all phases of the extended model which contains the previous stages along with remanufacturing.

The study attempts to *identify* and *quantify* the magnitude of the environmental impacts affecting each individual category evaluated by the software tool. Also, the study intends to verify if there is any ecological benefit or liability by incorporating remanufacturing, ,as one of the life cycle stages, into a typical production system. The software results will support the criteria utilized to determine whether or not remanufacturing is a viable production alternative leading to less ecological impact.

The proposed tool to conduct the experiment is the EPA's software package named TRACI. By using TRACI, the data entered into the software were analyzed to calculate: 1) mixed energy consumption (fossil fuel and [1]electricity), 2) greenhouse gasses emissions released (to air and water) during all stages of the product life cycle, 3) chemical emissions releases (to air and water) associated with every stage of the product life cycle and 4) water consumption along the different life cycle stages.

The environmental categories evaluated by the software include 1) ozone depletion, 2) global warming, 3) smog formation, 4) acidification, 5) eutrophication, 6) human health cancer, 7) human health non-cancer, 8) human health criteria pollutants, 9) eco-toxicity, 10) fossil fuel depletion and 11) [2]water use. Different chemical releases affect different categories. Therefore, different characterization factors are assigned to every chemical affecting individual categories to quantify the magnitude of environmental impacts.

[1] Due to software limitation all the energy coming from electricity sources had to be converted to energy based on fossil fuels (coal, oil and natural gas).

[2] The new version of the software (TRACI 1.1) does not include water use as one of the environmental categories. For that reason, calculations for this category were performed using TRACI.

In the event, that the same chemical affects more than one category, the software itself will assign different characterization factors for each group. The 11 environmental categories studied in TRACI will constitute the comparison parameters to identify which approach– manufacturing Vs remanufacturing- is less detrimental to the environment.

Given that the materials selected present different characteristics and experience different processes exclusive of each material, singular assumptions will be considered per material as necessary. These assumptions refer to materials properties, recycling capabilities and material resistance to cleaning technologies. The basics of the manufacturing process per material it will be explained, along with all processes included per stage. All materials will follow the sequence encountered in the two diagrams represented in the graphics 4.1 and 4.2 corresponding to the traditional LCA model and the extended LCA model respectively. Also, the recycling stage will be evaluated only in the materials that recycling has proved to be a feasible option.

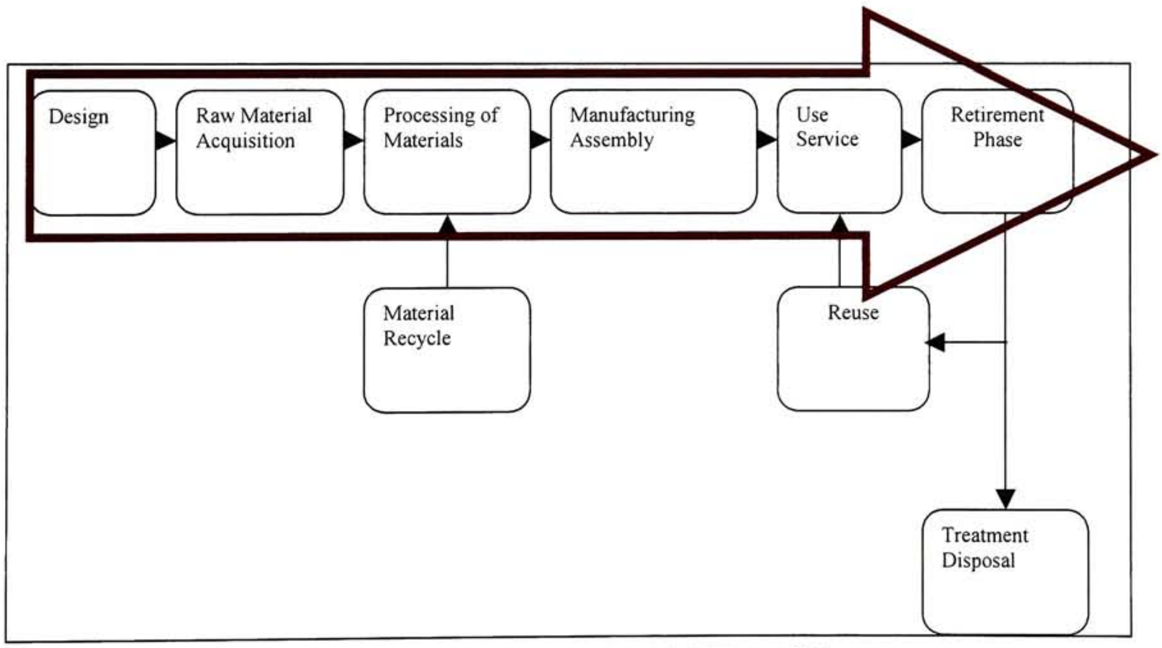


Figure 4.1 Traditional LCA Model (EPA, 1993)

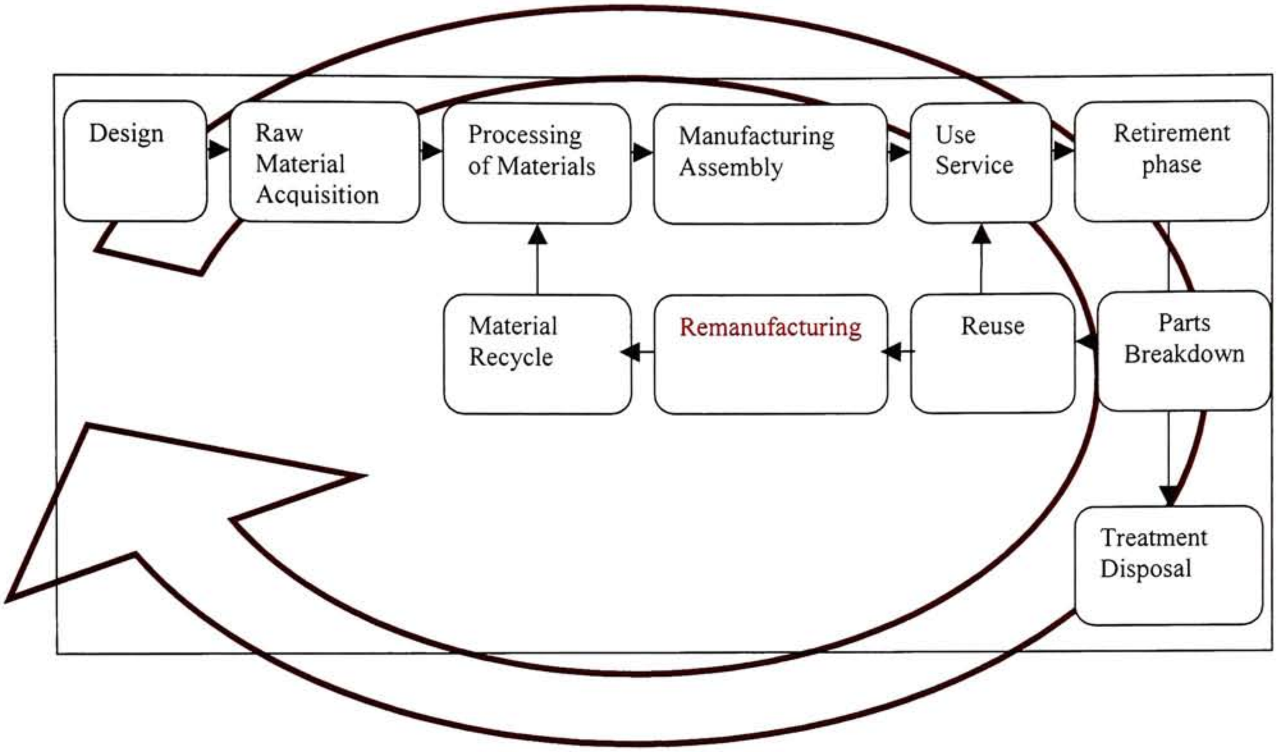


Figure 4.2 Extended LCA Model (Source: NCR[3])

Data were collected for each of the materials, including all processes involved in its manufacturing. Emissions for greenhouse gasses to air and water were gathered, along with energy consumption and water consumption. After colleting the necessary data per material, data were entered into TRACI and calculations were performed. The LCI data presented for each one of the materials is based in the units of " kilogram of emissions/ kilogram of material processed"; for energy " Mega Joule/kilogram of material processed"; and for feedstock " kilogram of fossil fuels/kilogram of material processed"

4.2 Aluminum Material

Aluminum is the second most abundant element in the Earth's shell after Silicon. Commonly found mixed with other elements, the mineral must be processed to recover its pure form. Aluminum is a remarkable material because of all its properties. Some of its main characteristics are: lightweight, high strength, recyclable, high electrical conductivity and its corrosion resistance. Specifically, the lightweight attribute has been attractive to various sectors including the automotive and aircraft industries. Fuel efficiency is related to the use of aluminum material in the automotive manufacturing industry, because of the weight reduction in vehicles. Besides automotive, numerous consumer products are made out of aluminum.

Energy consumption and pollution are the two main challenges being addressed by the aluminum manufacturing industry. Even though research development efforts have been performed to reduce the amount of energy consumption in the aluminum production environment, the metal still remains as one of the most energy-intensive materials to produce. One third of the cost to produce primary aluminum is associated with the use of energy. The reason for this high-energy consumption is the electricity required for the electrolysis and smelting processes. Also, additional energy coming from heating sources is required for melting, purifying and alloying processes. The total energy associated with primary aluminum production from bauxite ore was approximately 23.78 kwh/kg of aluminum in 2000; consisting of 8.20 kwh/kg aluminum for raw material and 15.58 kwh/kg aluminum, for electrolytic reduction. (The aluminum Association, 2000).

4.3.1 Primary Aluminum Production

Aluminum production begins with the extraction of bauxite (Al_2O_3), which is the typical raw material used for primary aluminum production. Bauxite generation occurs primarily in tropical and subtropical areas such as Africa, South America, and India, places known as locations where bauxite deposits are widespread. Consequently, the ore needs to be transported to other countries where the bauxite mineral is not easily found. After its removal, the bauxite is crushed and once compacted, the ore is ready to arrive to an alumina plant.

Aluminum production consists in two main processes, the Bayer process and the Hall-Heroult process. The Bayer process (fig 4.3) is mostly a refining step where the bauxite is crushed, washed, dried and converted into alumina.

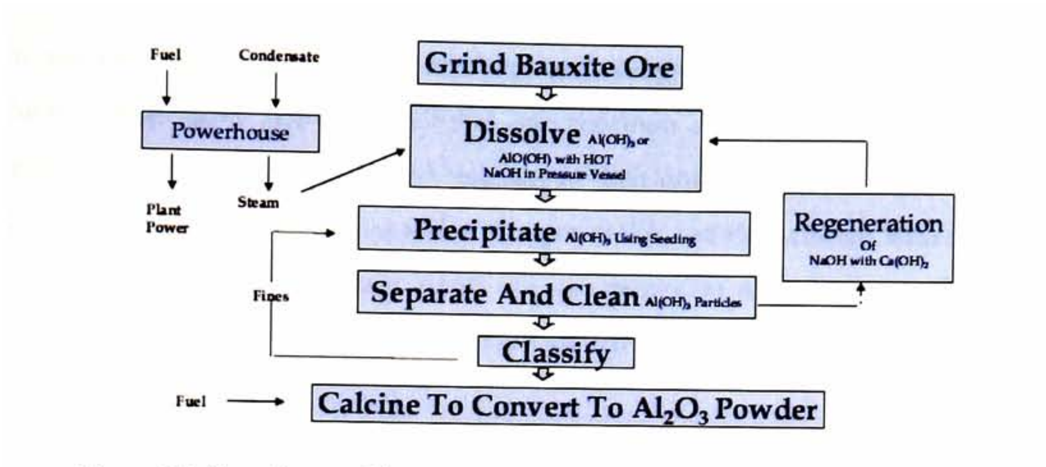


Figure 4.3 -Bayer Process Diagram for extracting aluminum oxide powder from bauxite ore. (Source: Kirk, R, E, et al. 1991. Aluminum, Wiley Interscience (Wiley)).

In this process the bauxite is combined with sodium hydroxide at high temperatures under steam pressure, and subsequently after a filtration and a separation process, alumina is the final outcome.

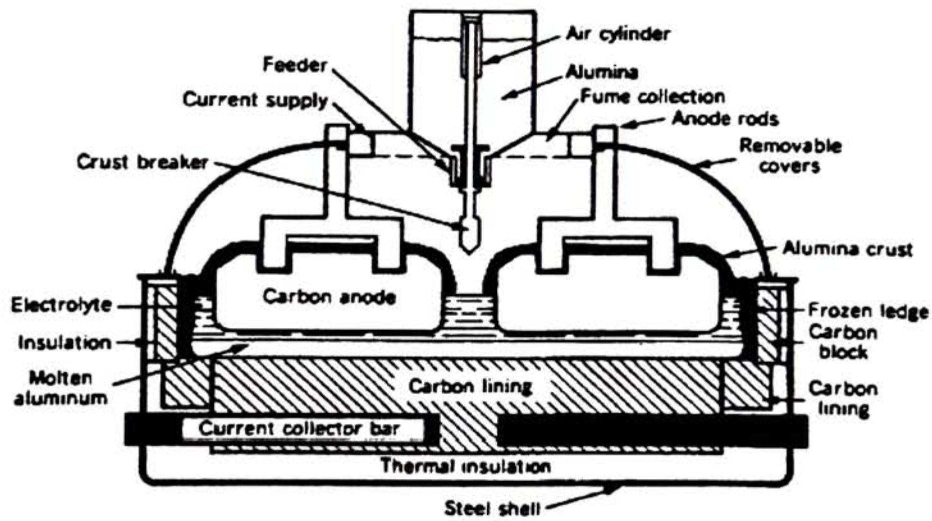


Figure 4.4 -Hall-Heroult Process Diagram for electrolytic smelting of aluminum metal. (Source: Kirk, R, E, et al. 1991. Aluminum, Wiley Interscience (Wiley)).

The Hall-Heroult process involves the electrolytic reduction of alumina where alumina is dissolved in a molten bath of fluoride compounds (the electrolyte). Direct current is applied to the bath, causing the alumina to separate into oxygen and liquid aluminum.

Electricity passes through the anodes, passes the molten aluminum and exits the cell through the cathode, causing the oxygen to react with the carbon anode which produces large amounts of carbon dioxide (CO_2) and carbon monoxide (CO).

There are two types of aluminum smelting technologies: "prebake" and "SÖderberg". Perfluorocarbon gases ($CF4$ and CF_2F_6) are common emissions resulting from these processes. These gases are of concern because of their potential to affect global warming. Molten aluminum is poured into a series of ingot molds and then cooled with water. After the casting process, the aluminum ingots are transported to manufacturing shops, where they are processed depending on the intended industry application.

4.3.2 Secondary Aluminum Production

The main component for the production of secondary aluminum is aluminum scrap. Being used as raw material, the scrap is pre-treated by shredding, magnetic separation and drying operations. The scrap is melted in oil or gas furnaces where substances affecting aluminum quality are removed. After the scrap is prepared for the smelting process, its treatment involves cleaning, melting, refining and alloying operations.

There are two different types of smelting processes. In one of the processes, the aluminum is smelted in rotary furnaces under a salt coat where the salt can be reused. In the other process, smelting is performed in induction furnaces and hearth furnaces, where less salt is needed. But, this type of process is just relevant for high-quality scrap. Aluminum refining may be necessary depending on the desired industry application because hazardous methods and toxic substances are usually involved in this process. Indeed, the energy consumption for secondary aluminum production is significantly less than for primary production and as result, the air emissions associated with energy requirements are fewer.

Recycled aluminum only consumes about 5% of the energy required to produce primary aluminum; however, there are other tradeoffs encountered in aluminum recycling such as the difficulties in the post-scrap separation process and the hazardous substances arising from the decontamination process.

Fig 4.5- A 27-ton ingot made from 1.5 million used drink cans.

Figure 4.5 shows an aluminum ingot that was made by aluminum recycling.
1.5 million soft drink cans were utilized as material input to produce this 27-ton aluminum ingot.

4.3.3 Environmental implication for aluminum production

Aluminum is considered to be a sustainable material because it is highly recyclable. It can be recycled over and over again without degrading its properties, saving energy and raw materials. Environmental concerns for the aluminum production industry are mainly associated with energy consumption. Energy is expended by using equipment needed to access mineral deposits and for the transportation of the material to different processing facilities. But the most energy intensive process is smelting. For that reason, throughout the years, innovative technologies and practices have been explored in order to improve aluminum manufacturing.

Besides energy issues, aluminum production plants release toxic air pollutants, including antimony, arsenic, lead, cadmium, nickel and acid gases. As a consequence, the exposure to those toxic air pollutants may cause health effects such as cancer, respiratory deficiencies and damage to the nervous system. During die casting operations, smoke is released from the molten aluminum shot process. These air emissions are concerning to workers and occupational institutions such as OSHA. Environmental organizations like EPA require companies to report all the air emissions resulting from aluminum manufacturing. The Toxic Release Inventory (TRI) reports all air emissions associated with the different processes utilized for aluminum production. The TRI report is one of the most important environmental documents that the manufacturing industry prepares each year as a way to provide detailed information concerning toxic pollutants emitted to air and water.

The transportation energy associated with raw material acquisition accounts for a large portion of the total energy needed for product manufacturing. In the case of aluminum, bauxite has to be mined in foreign countries and has to be transported to refining plants, resulting in extra energy being consumed by transportation. This type of energy might vary depending on the place where bauxite is extracted. Due to this uncertainty related to energy required for raw material transportation, this energy is not accounted for the purpose of this study. However, other transportation requirements such as transportation for aluminum ingots and transportation for final product distribution are taken into account when performing the LCA.

4.3.4 Aluminum LCI

Certainly, of the three materials evaluated in this study, aluminum production is the most energy intensive, meaning that its manufacturing requires major amount of energy for processes and operations related to the metal production. The summary table shows the energy required in each one of the stages necessary for primary aluminum production.

Energy- per kg of aluminum	**Units**	**Bauxite**	**Alumina Refining**	**Anode Production**	**Smelting Electrolysis**	**Ingot Casting (For primary Aluminum)**
Total	**MJ**	**0.480**	**20.604**	**56.819**	**112.446**	**5.458**
Renewable = hydro	MJ	0	0.357	0.426	55.720	0.737
Non-renewable= fossil based energy	MJ	0.480	20.247	56.393	56.676	4.721
Derived from:						
Coal	MJ	0.002	4.342	0.779	41.515	0.549
Oil	MJ	0.477	6.626	6.489	1.543	1.620
Natural Gas	MJ	0	9.279	5.079	13.618	2.552
Feedstock	MJ	0	0	44.046	0	0

Table 4.1- Life Cycle Inventory for primary aluminum production (Year 2000 Aluminum LCI Report for International Primary Aluminum Institute, March 2003)

Table 4.1 shows that the most intensive energy consumption occurs in the smelting process with 112.446 MJ/kg, followed by the anode production step with 56.819 MJ/kg. To produce only 1 kg of aluminum requires spending 195.807 MJ (mega joules) of energy along all the stages. Since TRACI only offers the possibility of inputting energy in form of fossil fuels (coal, oil and natural gas), energy that are not derived from fossil fuel sources such as nuclear energy were not included for the purposes of this study. As a result of this software limitation, [3]renewable energy had to be converted into fossil fuel energy based.

[3] Refer to appendix B to understand energy conversions.

Greenhouse gases associated with energy requirements includes carbon dioxide, carbon monoxide and nitrogen oxides. Table 4.2 shows the outputs related to these energy requirements.

Process/ Emissions	Bauxite Mining	Alumina Production	Anode Production	Electrolysis	Ingot Casting	Total (kg)
Nitrogen Oxides	____	2.24E-03	1.30E-04	3.50E-04	1.20E-04	2.84E-03
Sulfur Oxides	____	1.02E-02	7.00E-04	1.36E-02	2.00E-04	2.47E-02
Mercury	____	2.00E-07	____	____	____	2.00E-07
(w) Mercury	____	1.80E-06	____	____	____	1.80E-06
Benzo(A)Pyrene	____	____	1.00E-04	5.00E-03	____	5.10E-03
CF4	____	____	____	2.20E-04	____	2.20E-04
C2F6	____	____	____	2.10E-05	____	2.10E-05
HCI (Hydrogen Chloride)	____	____			6.70E-05	6.70E-05
CO2	0.048	0.99	0.849	9.78	0.368	1.20E+01

Table 4.2 -Air and Water emissions associated with the production of 1 kg of aluminum. (Year 2000 Aluminum LCI report for the International Aluminum Institute- March 2003)

Other LCA stages for aluminum material were evaluated according to the process sequence and the manufacturing operations required to fabricate an automotive water pump. Inputs and outputs of aluminum material are presented in the next graphic.

Figure 4.6 shows a LCI for all energy consumption involved in the primary aluminum process. It should be noted that electrical energy was converted to fossil fuel energy due to software limitations.

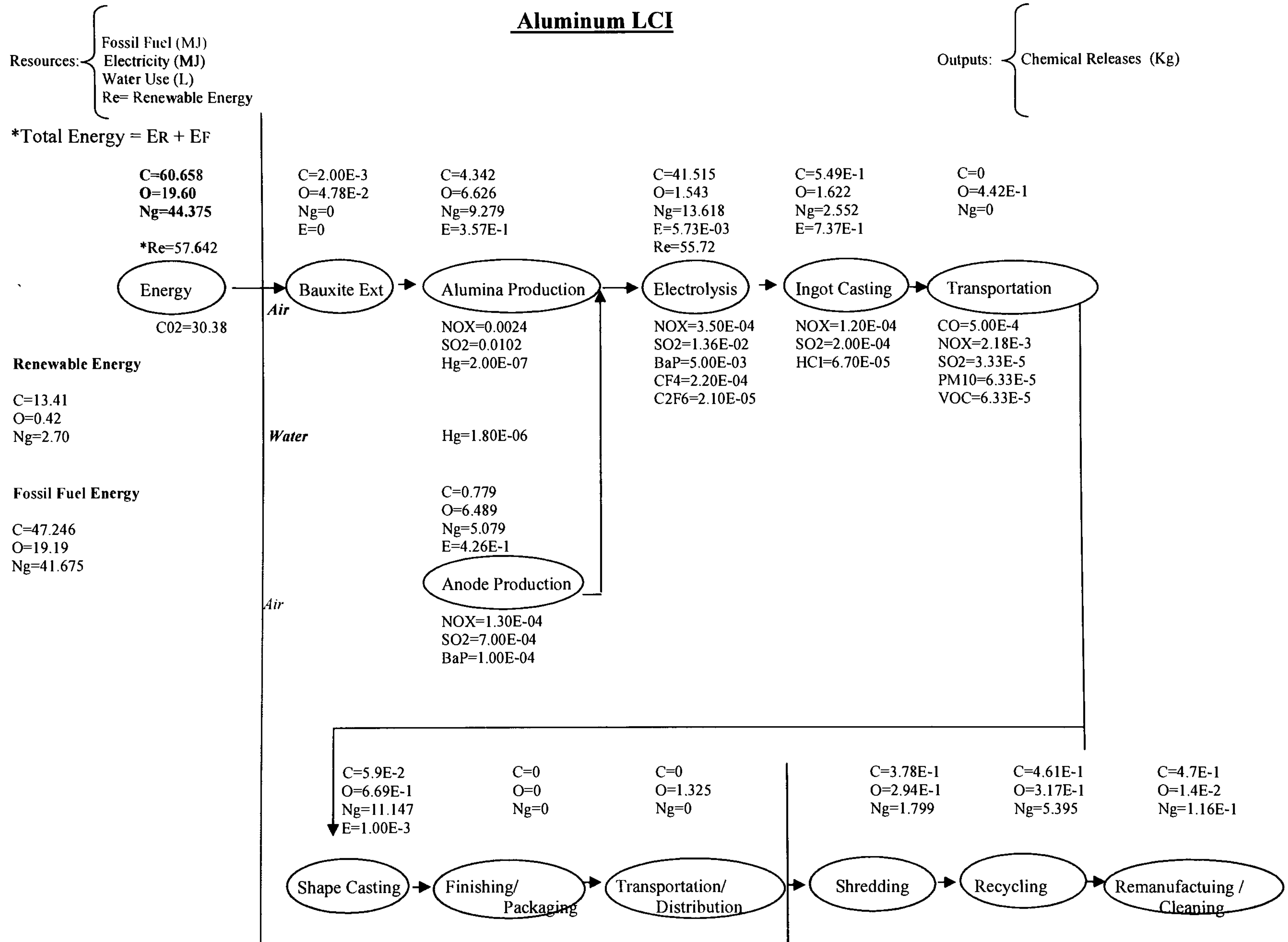


Figure 4.6- LCI for aluminum material including in the stages all processed required for an automotive water pump manufacturing and remanufacturing. To produce 1 kg of Aluminum.

4.4 Steel Material

Through the years, steel material has been used for an infinite number of applications including the automotive, construction, and packaging industry. Characterized for its strength, ductility, and corrosion resistance, steel was used first for railroads and now is widely used for bridge construction. In addition, steel constitutes one of the leading materials in the food packaging industry. The Steel industry uses a great deal of energy for its processing. In Japan, steel production accounts for 10% of the total energy consumption. The fact that steel is 100% recyclable makes the material a cost-effective and energy efficient option over other material choices. By recycling steel the extraction of natural iron and hard coal is avoided. Also, the emission of carbon dioxide is significantly reduced.

4.4.1 Steel Manufacturing

Two procedures dominate the steel manufacturing industry. The first one is called "Integrated" and the second one is the "Mini-mill". The main difference between the two technologies is the type of input (iron) that they consume for the manufacturing process. In the integrated procedure, iron is mainly used along with a small portion of scrap. In this configuration 70% of the input material is iron and the rest (30%) is scrap metal. The first step consists of making the iron, and subsequently this iron is converted into steel, using raw materials such as iron ore, coal, limestone, water, oil, alloys, steel scrap and energy. In the basic oxygen process molten iron from a blast furnace and iron scrap are refined in a furnace by injecting pure oxygen. Then, the oxygen reacts with carbon and this reaction provokes the formation of large amounts of carbon dioxide, usually controlled by extractors and cleaning devices. The integrated steelmaking route accounts for approximately 60% of world steel production.

The following figure illustrates process previously described.

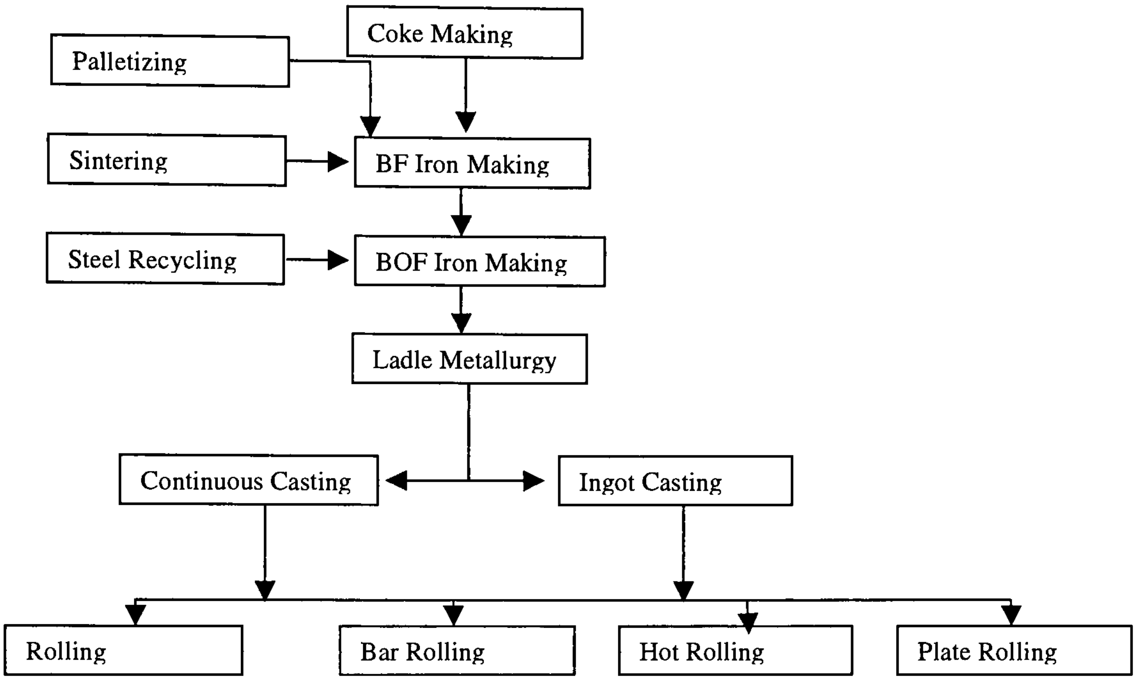


Figure 4.7 Process flow diagram for steel production using the blast furnace route. (Integrated procedure). (*Source*: International Iron and Steel Institute,2002)

As shown in the figure 4.7, iron from the blast furnace is converted to steel in the Basic Oxygen Furnace (BOF) and shaped into ingots by a casting operation. The nature of the ingot depends on the intended application. As can be observed in the previous figure, four different types of rolling processes can be performed to the ingot, in order to obtain different material properties and sheet sizes.

For the mini mill method, the main component is steel scrap. Steel is made in an Electric Arc Furnace (EAF) by melting recycled scrap. Subsequently, the chemical composition of the material is adjusted by adding alloying elements in a ladle furnace (LF). This type of furnace is used to produce carbon and alloy steel. The input material in this technology is typically 100% scrap. The energy required for melting processes comes from electricity; however, this energy can be replaced by injecting fossil fuels, and oxygen directly in the EAF.

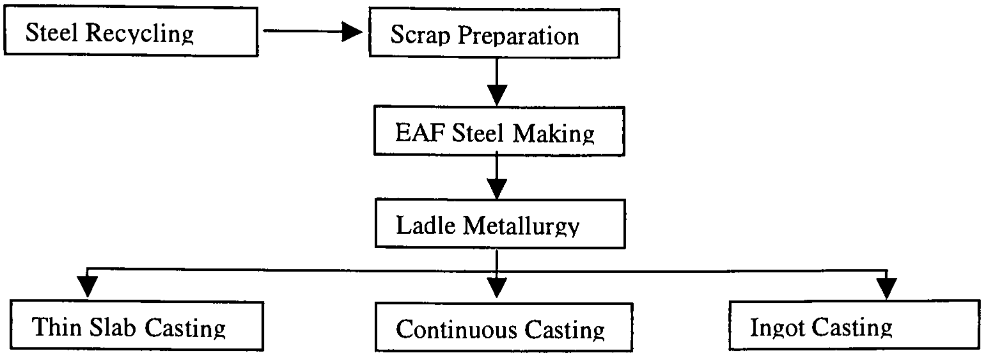


Figure 4.8- Process flow diagram for steel production using the electric arc furnace route. (Mini-Mill Procedure. (*Source*: International Iron and Steel Institute,2002)

Figure 4.8 provides an illustration of the EAF process description. This process represents a better option for the environment than the BOF because iron extraction is avoided. Many countries that cannot make iron by the traditional Blast Furnace route but have enough supplies of steel scrap are utilizing the EAF process to make steel.

A third technology is called Open Hearth Furnace (OHF) in which scrap and molten iron are refined into steel. This process accounts only for 4% of the world crude steel production. Countries where this procedure is employed include Russia, Ukraine, Poland, India, Turkey, etc.

4.4.2 Steel and the Environment

Operations for steel manufacturing have the potential to cause several impacts on the environment. The magnitude of those impacts depend on the types of operation and technologies employed to produce the metal. In the 1950s and early 1960s the steel industry was a major source of pollution, but improved designs have resulted in a reduction of emissions to air of 50% to 80% over the last 20 years. (International Iron and Steel Institute, 2002).

Similar to other metal industries, air pollution from steel manufacturing is linked to energy consumption and water management. Frequently, the water waste resulting from cooling and cleaning operations contains particulate matter and heavy metals such as cyanide, ammonia, etc. Consequently, in the event that air and water pollution cannot be prevented, emissions should be captured at the production site in the most effective way.

Several basic treatments are applied to most steelmaking plants worldwide including clarifiers for the solid removal; filtration for oil removal; chemical precipitation for metal removals, etc. In the blast furnace process, air emissions are generated especially when performing casting operations. During the casting process, iron oxides, magnesium oxide, and carbonaceous compounds are generated. Also, emissions resulting from the BOF process depend on the grade of the scrap used. Iron oxide is the predominant component of the emissions and particulates emitted during the steel making process. Emissions control techniques include emissions capture systems and gas cleaning systems. Some of these techniques consist of a duct attached to a hole in the furnace roof, which absorbs the emission to a gas cleaner, making the same function as a fume extractor does. In the EAF the operations that generate emissions are melting, refining, charging scrap and tapping steel. Air emissions from iron manufacturing in a blast furnace include particulate matter (PM); sulfur oxide (SOx), nitrogen oxides, and carbon monoxide resulting from sintering operation. Major pollutants in wastewater generated from steel production using BOF include suspended solids, chromium, cadmium, zinc, and fluoride.

In order to protect the environment, occupational institutions that are concerned with workers health have established emissions limits. Europe is a pioneer by creating emissions standards and environmental legislations. These boundaries have been created as a way to control air and water pollution resulting from manufacturing practices. Subsequently, these air emissions and effluents have to be reported for industries and monitored by the appropriate authorities. Two of the objectives of monitoring these pollution levels are: 1) to collect the data necessary to take corrective actions and 2) to collect the data for future comparisons and emissions estimates.

4.4.3 Steel LCI

For steel production (BOF)

INPUTS	UNITS	AVERAGE
Coal	Kg	0.589
Oil	Kg	0.0469
Natural Gas	Kg	0.0402
[4]Renewable Energy	MJ	0.352
Water Use	Liter	12.0

Table 4.3 -LCI for the inputs required for the production of 1 kg of steel. (The Steel Industry Sector Report-UN World Summit, 2002)

In table 4.3 the renewable energy and the fossil fuel energy are presented. Also, is shown the water consumption for the production of one kg of steel. It should be noted that this data belongs to the blast furnace route.

Steel Production

STEEL PRODUCTION	KG
Carbon Monoxide	2.64E-02
Nitrogen Oxides	2.18E-03
Sulphur Oxides	2.19E-03
(w) Ammonia	1.00E-04
(w) Chromium	2.00E-05
(w) COD	1.88E-04
(w) Lead	1.28E-07
(w) Nickel	9.30E-08
(w) Nitrogen	4.92E-05
(w) Phenol	5.20E-06
(w) Phosphate	1.72E-06
(w) Phosphorus	6.73E-07

Table 4.4- LCI of the outputs resulting for the production of 1 kg of steel. (The Steel Industry Sector Report-UN World Summit, 2002)

In the table 4.4 the different emissions resulting for the manufacturing process of steel material are presented. For the Case study analysis CO2 related to energy consumption is also estimated.

[4] The renewable energy required for steel material manufacturing was converted into fossil fuel energy based.

4.4.3 Steel LCI

For steel production (EAF)

INPUTS	UNITS	AVERAGE
Coal	Kg	0.0750
Oil	Kg	0.0583
Natural Gas	Kg	0.0556
[5]Renewable Energy	MJ	0.93
Water Use	Liter	7.19

Table 4.5 -LCI of the inputs required for the production of 1 kg of steel. (The Steel Industry Sector Report-UN World Summit.2002)

The table 4.5 shows the corresponding data for steel production in EAF. These requirements in terms of fossil fuel and energy are much less than in the BOF steel production pathway.

Steel Recycling

Outputs	Kg
Carbon Monoxide	2.37E-03
Nitrogen Oxides	1.53E-03
Sulphur Oxides	1.98E-03
(w) Ammonia	7.85E-07
(w) Chromium	2.70E-08
(w) COD	3.14E-05
(w) Lead	9.20E-08
(w) Nickel	6.80E-08
(w) Nitrogen	1.13E-06
(w) Phenol	3.08E-08
(w) Phosphate	3.08E-06
(w) Phosphorus	6.50E-05

Table 4.6- LCI of the outputs resulting from the production of 1 kg of steel. (The Steel Industry Sector Report-UN World Summit.2002)

The table 4.6 illustrates the chemical emissions resulting for the steel production in the EAF route. Similar to inputs, the emissions in this scenario are less than for BOF.

Figure 4.9 shows a LCI for all energy consumption involved in the steel production process for producing 1 kg of steel.

[5] The renewable energy required for steel material manufacturing was converted into fossil fuel energy based. The energy in terms of coal, oil and natural gas can be observed in the figure 4.9

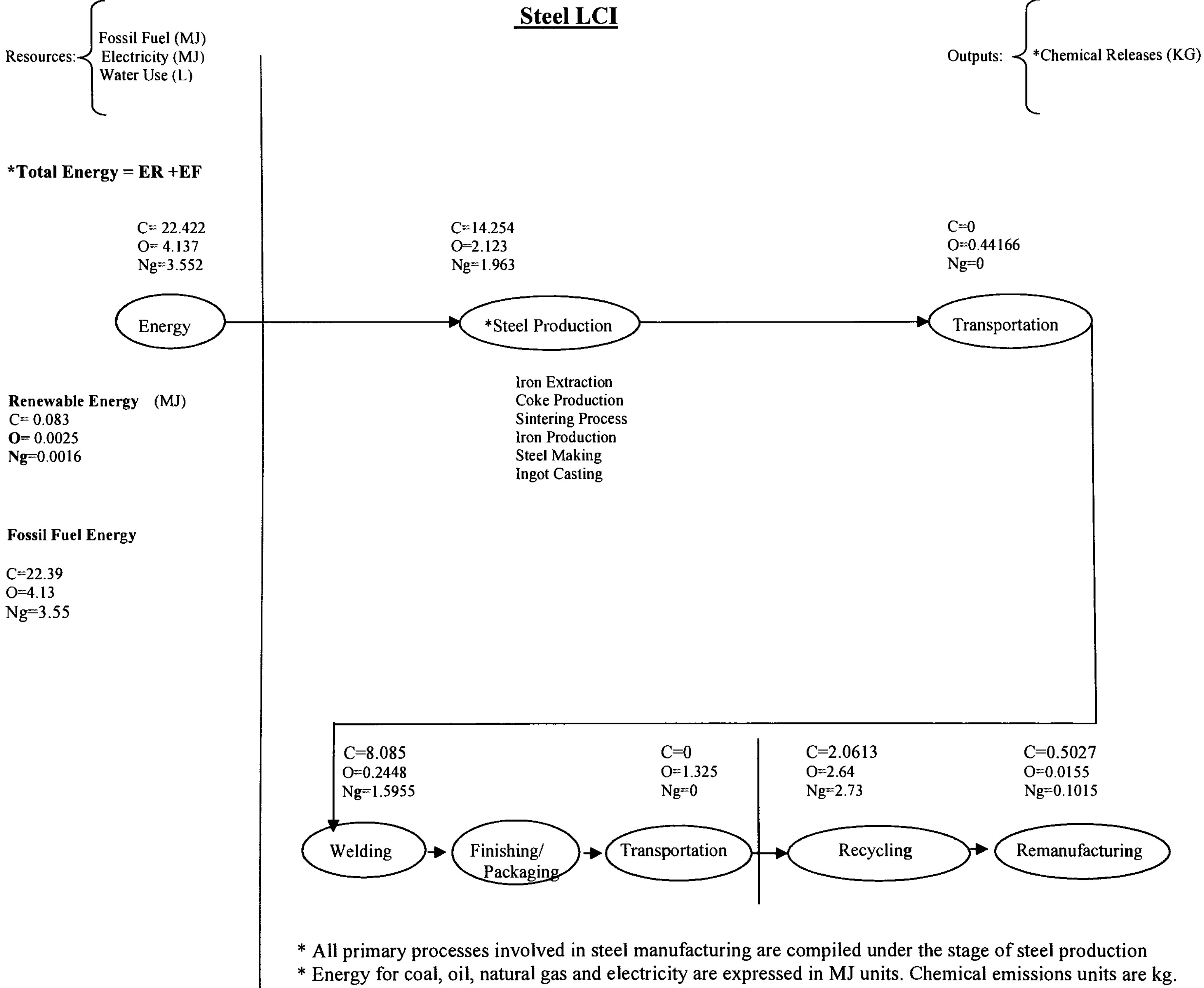


Figure 4.9- LCI for steel material including in the stages all processed required for an automotive water pump manufacturing and remanufacturing. To produce I kg of steel

4.5 PVC Material

Polyvinyl Chloride (PVC) is a type of plastic used in many industries and for several applications including automotive parts, toys, medical supplies and packaging. PVC is considered a leading plastic material for the construction market, examples of its application in this sector include pipes, flooring, windows, cable insulation, and house siding.

4.5.1 PVC Manufacturing

PVC production consists of five major steps: 1) ethylene and chlorine gas production, 2) feedstock production, 3) polymerization, 4) formulation and 5) molding. Ethylene gas is purified from petroleum or natural gas while chlorine is generated from sea salt passing by an electrolysis process, which requires an enormous amount of energy (about 3000 kwh/ton). These two gases are the major materials inputs for the production of PVC. Ethylene dichloride (EDC) is produced by combining ethylene and chlorine in a process called oxychlorination. Afterwards, EDC is converted into vinyl chloride monomer (VCM) by another chemical reaction called pyrolysis. The third step in the PVC production is called polymerization where VCM molecules are connected to yield polyvinyl chloride.

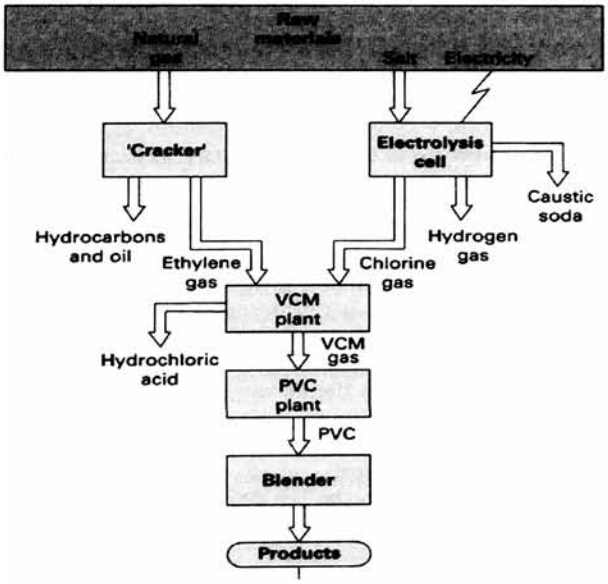


Figure 4.10 – The Production Process of PVC (Source: Institute of Polyvinyl Chloride)

When PVC is manufactured the plastic is mixed with other chemicals and additives to obtain several useful properties. Depending on the desired application, the polymer is mixed with additives and colorants to make it either flexible, moldable, or long lasting. Generally those additives are toxic compounds- lead, cadmium, zinc, chromium- that may have health impacts on workers and on the environment as well.
The final step after the combination of additives with the plastic is the molding process, where PVC is shaped into final products such as pipes, bottles, etc.

4.5.2 Environmental Implications for PVC Production

PVC material does not offer many options for safe disposal. In the same vein, PVC recycling has not proved to be a feasible alternative to treat the material after its use. Among all types of plastics, PVC has the lowest recycling rate, not even reaching 1%. In 1996, The American Plastics Council (APC) reported a recycling rate of 0.9 percent for PVC packaging and 2% percent for PVC bottles. Besides recycling, other disposal alternatives for PVC are landfill and incineration; however these two options are not good answers to the PVC disposal problem. When PVC is either land filled or incinerated hazardous substances have the potential to contaminate air and waste.

Since PVC is unique in its content with different and hazardous additives- including lead and cadmium- its separation and decontamination process from other plastics requires a high money investment for technologies, equipment and labor that is not always worth it for business. According to the Association of Post-consumer Recyclers (APR) in the US, "PVC bottles are a contaminant to the recycling of PET and HDPE bottles and have no place in post-consumer plastic bottle recycling"; meaning that PVC obstructs the recycling operation of other types of plastics. Impacts of PVC products depend not only on the material production but also on the desired application. There exists a general concern because toxic additives encountered in PVC products can be transferred from products to consumers, children and patients at hospitals. In addition, since PVC is used for construction, in any fire occurrence involving PVC products, hydrogen chloride may be released having the potential to kill occupants.

Given that the production of Chlorine requires a vast amount of energy, this process may create some environmental problems including global warming, acid rain, air pollution, mercury emissions, etc. Releases of EDC and VCM are potential hazards for communities. In 1999, a study conducted in Mosville, LA, revealed that dioxin levels in the soil were 50% higher than the limit allowed. Mosville is a community situated near various PVC manufacturing industries. According to OSHA, approximately 12.5 million people are exposed to EDC emissions from chemical manufacturing facilities in the United States and this situation represents a real concern because VCM is known as a human carcinogen. As VCM has been linked to human cancer-causes, regulations now require certain limits in emissions levels such 1-5 ppb for VCM.

One of the solutions proposed by industry to control the amount of PVC in the waste stream is the creation of long-life PVC products. By creating lasting PVC products the frequency of this material in our waste may decrease along with the environmental impacts associated with the hazardous materials.

4.5.3 PVC LCI

Beginning with the extraction of oil and rock salt for the production of EDC and VCM, energy consumption and mining equipment required for extraction operations might provoke major environmental impacts. Depending on the desired application, PVC can be made by three different processes: suspension, emulsion, and bulk. These names are related with the type of technology employed to manufacture the resin. Suspension PVC is used to make rigid PVC for applications such as building materials, pipes, and automotive parts. Emulsion PVC is mainly used for fabrics, while bulk PVC is specifically aimed for bottles.

From the three different resins processing, suspension PVC accounts for approximately 80% of the PVC market. Emulsion accounts for 13% and for bulk PVC for 5%. (European Council of Vinyl Manufacturers- May 1993). Given that the PVC parts encountered in the automotive water pump are rigid components, the suspension data is utilized in this study.

The energy included in the manufacturing of PVC material are described in next table.

-Inputs

FUEL TYPE	FUEL PRODUCTION & DELIVERY ENERGY (MJ)	ENERGY CONTENT OF DELIVERED FUEL (MJ)	ENERGY USE IN TRANSPORT (MJ)	FEEDSTOCK ENERGY (MJ)	TOTAL ENERGY (MJ)
EDC	9.74	4.78	0.07	0.00	**14.59**
VCM	8.6	6.11	0.04	0.00	**14.75**
PVC	8.45	4.10	0.035	0.00	**12.60**
Total	**26.79**	**14.99**	**0.145**	**0.00**	**41.95**

Table 4.7 Gross Energy in MJ required for producing 1 kg of suspension PVC. (Source: European Council of Vinyl Manufacturers- May 1993)

The table 4.7 comprises in detail all the energy used in the manufacturing process of the PVC material.

-[6]Feedstock Inputs

PROCESS/ FOSSIL FUEL	EDC	VCM	PVC	TOTAL
Coal (kg)	1.50E-01	1.25E-01	1.55E-01	**4.30E-01**
Oil (kg)	3.10E-01	3.70E-01	4.10E-01	**1.09E+00**
Natural Gas (kg)	3.10E-01	4.70E-01	5.25E-01	**1.52E+00**
Total	**7.70E-01**	**9.65E-01**	**1.09E+00**	**3.04E+00**

Table 4.8- Primary feedstock resources expressed in kilograms for producing 1 kg of PVC. (Source: *Eco-profiles of the European Plastic Industry.* European Council of Vinyl Manufacturers- May 1993)

Table 4.8 shows the feedstock necessary for the production of PVC. Interestingly, even though the feedstock's are expressed in terms of fossil fuels, they represent the ingredients necessary for the PVC material manufacturing.

[6] Feedstock: energy used for purposes other than for heat, power and electricity generation such as:
-natural gas processed to extract gases (like butane, ethane and propane) which may be used as raw materials to produce fertilizers and pharmaceutical products; and
-coal used by a steel maker as a raw material to produce coal coke.

-Outputs from PVC production

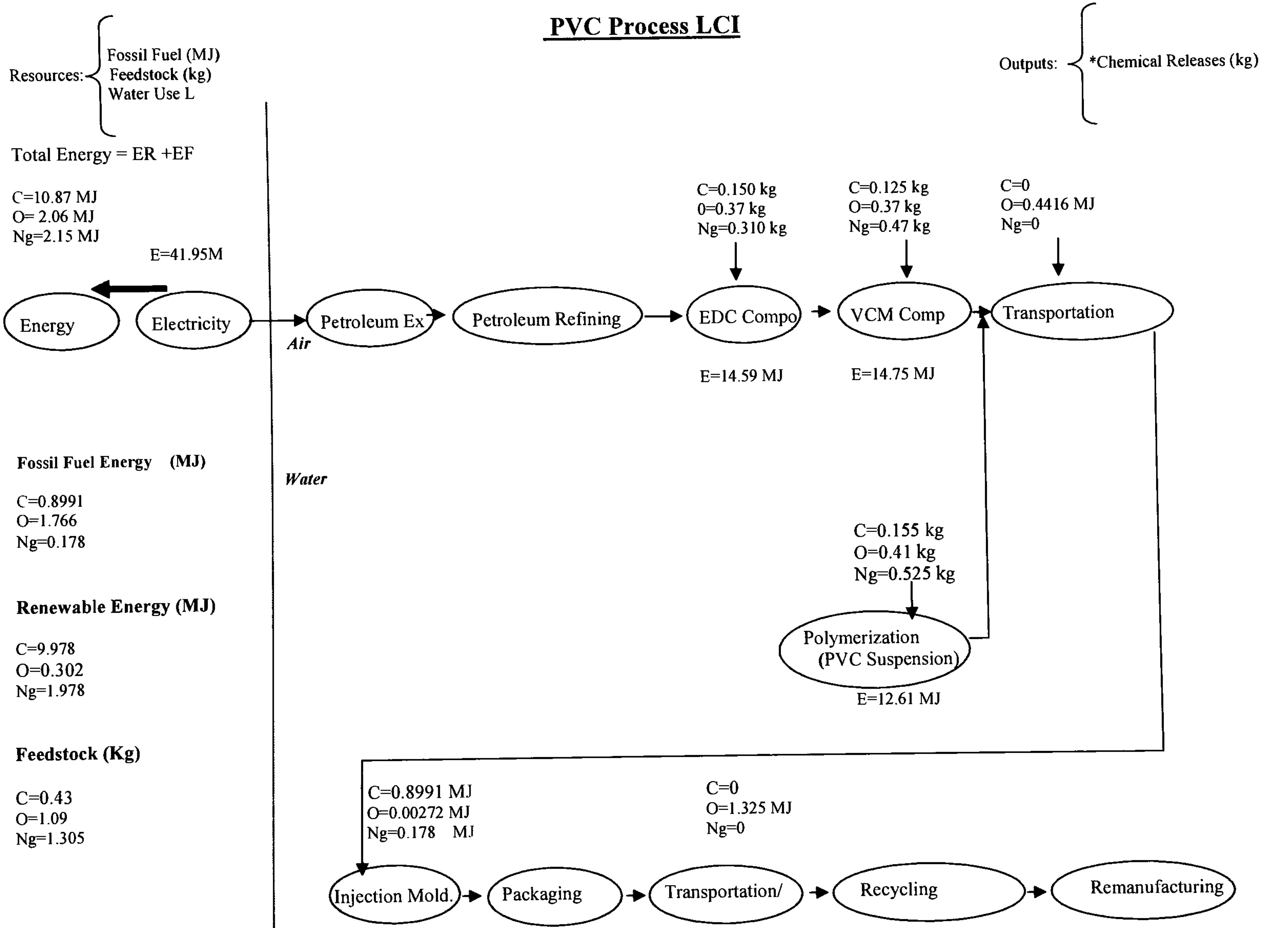
EMISSIONS (KG)	FROM EDC	FROM VCM	FROM PVC	TOTALS
Carbon Monoxide (CO)	6.00E-03	9.50E-03	9.50E-03	2.50E-02
Carbon Dioxide (CO2)	2.60E+01	2.13E+01	1.75E+01	6.48E+01
Sulfur Oxides (SOx)	5.00E-03	1.05E-02	3.65E-02	5.20E-02
Nitrogen Oxides (NOx)	3.00E-02	1.09E-01	9.90E-02	2.38E-01
Hydrogen Sulfide (H2S)	1.00E-03	2.00E-03		3.00E-03
Methane	7.90E-02	8.90E-02	9.15E-02	2.60E-01
Lead			4.00E-04	4.00E-04
Mercury			7.00E-04	7.00E-04
Dichloroidoethane (HCI)		5.25E-02		5.25E-02
Ammonia	1.30E-02	1.50E-03	4.15E-02	5.60E-02
VCM	6.00E-03	6.60E-02	1.64E-01	2.36E-01
VOC	2.00E-03	1.00E-03		3.00E-03
Ethylene	1.20E-02	1.50E-03		1.35E-02
(w)COD	1.80E-01	4.65E-01	1.13E+00	1.78E+00
(w)BOD	1.90E-02	3.65E-02	2.12E-01	2.67E-01
(w) Phenol	4.00E-04	4.00E-04	4.00E-04	1.20E-03
(w) NA	6.30E+01	2.10E+01	1.69E+01	1.01E+02
(w) Iodomethane	1.00E+02	4.10E+01	4.15E+01	1.83E+02
(w) SO4	1.50E+00	2.10E+00	3.10E+00	6.70E+00
(w) Phosphate	3.00E-03		5.85E-02	6.15E-02
(w) Arsenic		4.00E-04	4.00E-04	8.00E-04
(w) VCM	1.00E-03	4.00E-04	2.50E-03	3.90E-03

Table 4.9 -Gross air and water (w) emissions in kg associated with the production of 1 kg of PVC (Source: *Eco-profiles of the European Plastic Industry.* European Council of Vinyl Manufacturers- May 1993)

Table 4.9 indicates the chemical releases associated with PVC production.

Since PVC water pump components are not suited to be recycled or remanufactured, there is no data for PVC recycling and PVC remanufacturing.

Figure 4.11 shows a LCI for all energy consumption associated with the PVC production process for producing 1 kg of PVC.



* Petroleum extraction & petroleum refining energy consumption is already included in the EDC, VCM, and PVC process.
* PVC requires feedstock inputs directly into EDC, VCM and PVC production stages.

Figure 4.11 LCI for PVC material including in the stages all processed required for an automotive water pump manufacturing and remanufacturing. To produce 1 kg of PVC

4.6 Automotive Water Pump Case Study

In the automotive sector, remanufacturing has represented a cost-effective alternative to replace worn or damaged parts. Remanufactured parts are sold for 25 to 40% less than new parts. Common automotive parts being remanufactured in the actual market include alternators, clutches, carburetors, fuel injectors and water pumps; because of their low repair costs. In spite of the evident economic benefit of the remanufacturing alternative, some consumers still hesitate to accept that remanufactured parts provide as good quality as new units. Sometimes, the remanufactured parts and the components to be replaced, make the final product have a better performance than the original one.

One downside of the remanufacturing industry lies in the fact that there are not standards to regulate the remanufacturing industry. For example, when remanufacturing a water pump, some remanufacturers may reuse the entire seal because it does not present any imperfection, while other remanufacturers will automatically replace the part as a strategy to add value and quality to the final product outcome. In either case, the main concept is to recondition the part to the original specifications and to offer the consumer a certain level of reliability.

In the same order, some efforts have been made to understand important issues affecting the automotive remanufacturing industry and to contribute to the creation of general standards. One of these efforts was the survey named "Issues in the Automotive Parts Remanufacturing Industry- A Discussion of Results from Surveys Performed among Remanufacturers" International Journal of Engineering Design and Automation, 1998 where the intention was to identify and characterize typical problems and challenges faced by automotive remanufacturers. Three surveys were conducted for this study and the questions addressed issues such as remanufacturing costs, disassembly techniques, part reassembly, and inspections strategies.

The survey results indicated that the remanufacturing industry is still working on the incorporation of innovative technologies and production practices to enhance performance and reliability in the automotive remanufacturing sector.

Cleaning was identified as one of the highest cost contributors to remanufacturing, emphasizing that the main cause for cleaning costs are all the environmental regulations that they have to follow in order to meet requirements established by EPA and other occupational agencies. Also, they agreed that designers need to become conscious about the necessity of creating products to be remanufactured and to make the disassembly phase more practicable to save time and use current mechanisms utilized by automotive industry.

4.6.1 Product: Automotive Water Pump

The automotive sector represents the largest fragment (57%) of the United States remanufacturing industry. All parts encountered in an automotive water pump are made out of five different materials. These materials are aluminum, steel, plastic, rubber and ceramic. The first three materials –aluminum, steel and plastic- represent [7]99% of the weight of the components encountered in a automotive water pump used for this study and the biggest parts are made out of aluminum and steel. The total weight of the water pump is 2.041 kg, where aluminum accounts for a 53% (1.078 kg); steel accounts for 46% (0.942 kg) and PVC plastic for 0.3% (0.007 kg). Since these materials represent almost the entire water pump, the analysis explored in this paper is based on these materials. Ceramic and rubber can be found in the water pump seal as small components that are never remanufactured in practice. Materials are distributed within parts as following: the pump housing is made of aluminum material; the bearing assembly, the shaft, the ball bearings and the impeller are made out of steel parts; and the water pump seal contains plastic, steel, rubber and ceramic rings. The seal is the part with most different materials included.

The following figure 4.12 refers to the automotive water pump bill of materials.

[7] Refer to bill of materials. Figure 4.12

Water Pump
Bill of Materials

#	Part Name	# of parts	Material	Process	Part weight (g)	(kg)
1	Pulley Mounting plate	1	Steel	Fine Machining	260	0.26
2	water pump housing	1	Aluminun	Die Casting	1078	1.078
3	Water inlet hose	1	Steel	Forging, deformation, forming	0	0
4	Water outlet hose	1	Steel	Forging, deformation, forming	0	0
5	Impeller	1	Steel	Sheet metal forming, welding	92	0.092
6	Shaft	1	Steel	Machining , grinding	213	0.213
7	Shaft Bearing	1	Steel	Machining , grinding	351	0.351
8	Ball Bearings	12	Steel	Centreless Microgrinding	12	0.012
9	Ball Bearing Separator	2	Plastic	Injection Molding	2	0.002
10	Grease				Lithium Grease	
11	Gasket	1	Paper		0	0
12	Ball Bearings Cover	2	Plastic	Injection Molding	2	0.002
13	Seal					0
	a -cup	1	Galvanized Steel	Forming	12	0.012
	b -Metal Spring	1	Steel	Forming	8	0.008
	c - Rubber band	2	Rubber	molding	2	0.002
	d - Metal ring	2	Steel	Micromachining, Stamping	2	0.002
	e -Plastic Ring	1	Plastic	Injection Molding	3	0.003
	f -Ceramic Ring	1	Ceramic	Press, Centreless, Grinding, Lapping	4	0.004
14	Packaging	1		Assembly		
	Total				**2041**	2.041

Figure 4.12 - Bill of material for an automotive water pump.

4.6.2 Water Pump Description

The water pump constitutes one of the essential parts of an automotive cooling system. The primary job of the cooling system is to keep the engine from overheating by transferring heat to the air. A typical engine cooling system requires removing about 20% of the total heat generated by the car engine. Generally located on the front of the engine, the water pump is used to circulate coolant through the engine. Its main function is to push and draw coolant. The pump circulates fluid whenever the engine is running and this fluid is generally 50% cooler than the operating temperatures of the engine.

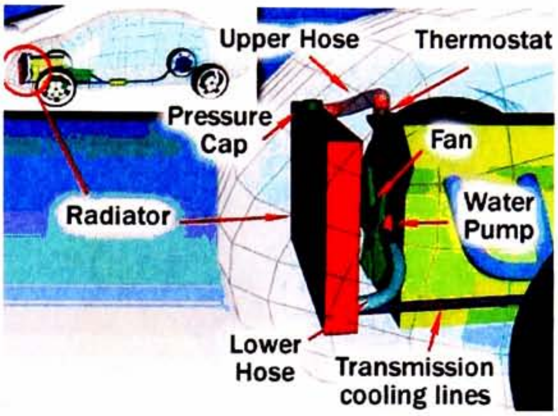


Figure 4.13- Diagram of an Automotive Cooling System. How stuff work (www.howstuffworks.com)

The figure 4.13 shows a diagram containing all components of an automotive engine and its cooling system.

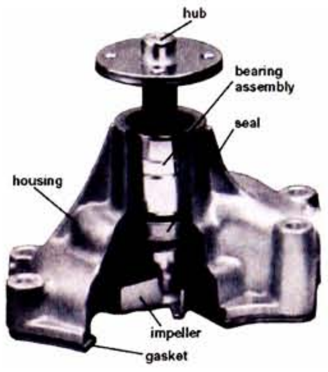


Figure 4.14 Water Pump parts (Source: Gates Water Pumps, 2003)

Figure 4.14 shows an automotive water pump and its main parts. Five components make up the water pump construction including housing, shaft (hub), impeller, bearing assembly, seal and gasket.

1) The *hub* (also called the shaft) is attached to the bearing assembly and to the source of power (a belt and pulley) to provoke the rotation of the impeller. 2) The *housing* is typically made of cast iron or aluminum and lately as a common trend manufacturers are choosing aluminum instead of steel, to reduce vehicle weight. 3) The *impeller* is the mechanism that pumps coolant throughout the system. 4) The *bearing assembly* supports the continuous rotation of the impeller. It has two sets of bearings; one near the front of the shaft and one near the rear. 5) The *seal* protects the bearing assembly from coolants and contaminants and 6) the *gasket* insures a tight, leak free interface between the thin impeller cavity (where coolant collects) and the housing body.

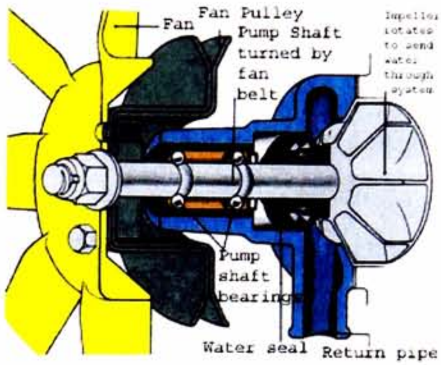


Figure 4.15 Water Pump Assembly

Figure 4.15 shows the water pump parts from an internal view. Ball bearing and other parts can be observed in detailed.

Each part's main function within the water pumps goes as following: The housing connects the impeller and the shaft bearing assembly being supported by the bearing assembly. The housing is machined or cast to allow the impeller to run close to the housing face, capturing coolant and creating a differential pressure through the pump. This pressure difference causes the coolant to be sucked up on the inlet side and be pushed away through the outlets. A pulley is mounted on the pump hub where the fan is attached. The ball bearings and the fluid (coolant) cannot coexist and the seal's main function is to keep them apart.

The seal contains a ceramic part in a round black piece of rubber and its function is to prevent coolant from escaping along the impeller shaft. An impeller is a round disc of metal with multiple blades or paddles about its circumference, containing a rear cover plate bolted to the housing that acts as a wall to keep coolant from escaping the impeller cavity. The impeller pushes the coolant through two passages into the engines block and the openings of the block allow coolant to flow around.
(www.indiacar.com/infobank/water_pump.htm).

4.6.3 Water Pump Failures

Water pump efficiency varies depending on several factors. These factors are related to the way each water pump component operates. Seals and ball bearings account for over eighty five percent (85%) of water pump failure; for that reason, both parts are normally replaced when remanufacturing an automotive water pump. Usually, a brand new water pumps last 60,000 miles or more, but it is necessary to do certain maintenance to avoid damages that may affect the pump efficiency. Generally, the main causes of premature failure are coolant contamination and system corrosion, problems that can be easily prevented by routinely checking the condition of the coolant.

Some of the common causes of a water pump failure are:

1) Bearing failure- rumbling and screeching noises coming from the water pump indicate a worn bearing, meaning that the pump needs to be replaced.
2) Seal failure- ceramic seal cracked by adding cold coolant to a hot system.
3) Broken housing- it is caused by heavy vibrations or imbalance.
4) Broken shaft- imbalance is the cause of this damage, intensifying by rapid acceleration and high revolutions.
5) Contamination- when the coolant is contaminated, particles of this contamination will destroy the water pump seal.
6) Defective Fan Clutch- when there is any kind of leakage (oil or water).

In addition to these patterns concerning water pump failure; running the pump dry will cause over-heating and excessive vibration problems that will shorten seal life.

4.6.4 Water Pump Remanufacturing Process

Once the water pump starts presenting operating problems, it must be replaced to keep the cooling system working properly. Usually, a consumer takes the car to a place to be fixed and the mechanic determines that the water pump is running inadequately. The water pump is uninstalled and collected for future remanufacturing. A general description of how this remanufacturing process occurs is explained in the following paragraphs.

When cores are transported to the remanufacturing center, the water pump is disassembled and then cleaned. Close inspection reveals whether or not any parts needs to be replaced to proceed with the remanufacturing operations as necessary. Usually, the housing, the hub, the bearings assembly and the impeller don't wear out and can be reused. These parts are thoroughly cleaned; inspected for any form of damage, and then they get a new protective finish. Ball bearings are tested and replaced with new ones when necessary. Some remanufacturers add a double bearing at the end, which significantly increase the load-carrying capability of the shaft. Then, tolerances are checked ensuring that the water pump itself is more efficient and that it's capabilities to pump fluid are better. Seals are replaced 100% with original equipment quality seals, and the "like new" assembly is ready for resale.

Given that all these remanufactured parts meet certain qualifications, many of them have the capacity to exceed the original specifications. Some of the benefits of this WP reconditioning process are based in the following points: 1) Old housing is reused and no new casting is required which can be translated into profitability for industry. 2) No production of aluminum/iron is required for remanufacture parts, avoiding energy consumption and the pollution associated with the material manufacturing processes. Clearly, this water pump remanufacturing process represents advantages in economy, ecology and energy conservation.

4.6.5 Water Pump Analysis

Manufacturing a water pump

The materials requirements corresponding to the water pump utilized through this study are: aluminum (1.078 kg), steel (0.942 kg) and PVC plastic (0.007 kg). Ceramic and rubber parts are not included in this analysis because they are never remanufactured. The bill of materials shows in detail how materials are distributed among all parts forming the water pump. Also, it presents the process necessary to elaborate each part.

MATERIAL	PART TO BE REMANUFACTURED	PART TO BE RECYCLED	PART TO BE DISCARDED	PART WEIGT (KG)
Aluminum	Pump Housing (1)			1.078
Steel	Water inlet/outlet			0.004
Steel	Pulley Plate (1)			0.26
Steel	Impeller (1)			0.092
Steel	Shaft (hub) (1)			0.213
Steel	Bearing Shaft (1)			0.351
Steel		Bearing Balls (12)		0.012
Steel		Metal Spring (2)		0.008
Steel		Metal Ring (2)		0.002
PVC			Ball Bearing Separators (2)	0.002
PVC			Ball Bearing Cover (2)	0.002
PVC			Plastic Ring Seal	0.003
Total				**2.027**

Table 4.10 Bill of materials corresponding to the Aluminum, Steel and PVC contained in a WP

Table 4.10 provides a bill of material only for the WP components utilized in this study.

In order to understand and visualize the route of each material into the product life cycle, the next graphic is presented.

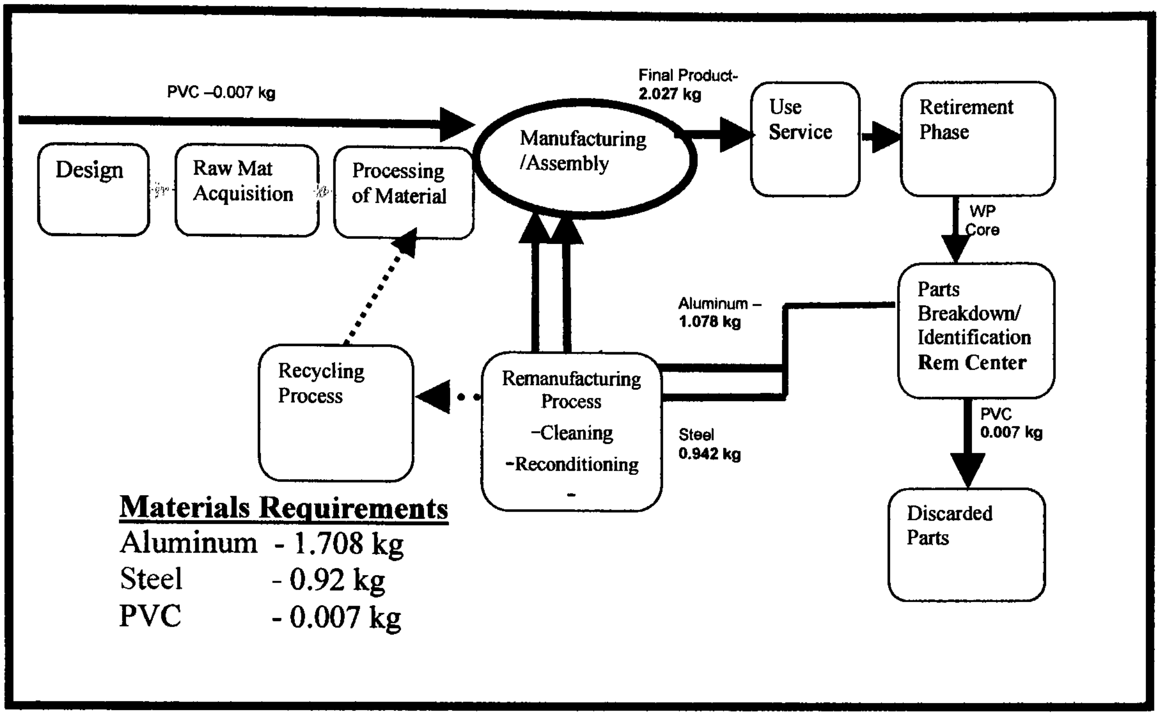


Figure 4.16 -Route of the materials in a remanufacturing process of a water pump.

Figure 4.16 shows, in detail, the sequence of steps needed for this remanufacturing process. The entire core – containing aluminum, steel, and PVC – weighting (2.027 kg) travels from the drop-off place to the remanufacturing center. The aluminum housing (1.078 kg) is remanufactured. The shaft (hub), the impeller and the bearing shaft represent the steel parts (0.92 kg) to be remanufactured. After these parts are reconditioned they are transported to the assembly facility. Other steel parts- ball bearings, metal spring and metal ring- weighting in total (0.22 kg) has to be recycled. These parts go from the remanufacturing facility to the recycling location and after being recycled they go to the manufacturing and assembly shop to be processed and converted into the parts they were previous to recycling. Some manufacturing processes-machining, grinding, deformation process- are performed at this point. Continuing with this description, the PVC material (0.007 kg) has to be discarded, and it needs to be re-produced. Regardless the processes and operations experienced, and after all parts are treated appropriately they are assembled all together in the assembly phase and transformed into the "like new" water pump that was before disposed. As observed in this description, the remanufactured piece requires additional transportation.

4.7 Transportation Flow

The following analysis explains all the implications that have been taken into account for the transportation flow. First, the transportation necessary to produce a water pump is evaluated and subsequently, the transportation required in a remanufacturing scenario is also evaluated to understand any differences encountered between both productions settings. Some assumptions have been taken to arrange the analysis:

1. Raw material transportation does not count for the purpose of this study.
2. Distance between facilities corresponds to an hour of commercial truck traveling.
3. Distance traveled per hour is approximately (60 miles).

In the United States, medium and heavy trucks are widely used as a main source of transportation for the metallurgical industry. EPA has specific parameters to differentiate "light- duty trucks", from "heavy-duty truck". A light truck weight from 6,000 to 8,500 pounds GVW (gross vehicle weight) including in this category pickup trucks, minivans, and sport-utility vehicles. Heavy-duty trucks are defined as vehicles of GVW above 8,500 pounds such as large pickups, buses, recreational vehicles and delivery trucks. In the state of California, heavy trucks must weigh above 14,000 pounds (for a car model year 1995 or later). For this analysis a heavy-duty truck weighing 80,000 pounds was utilized for metals and product transportation. The gas mileage of this truck is 6.7 miles per gallon (mpg). *(Source:* Fuel Saving for Heavy Trucks On Concrete Pavement in Canada . (www.concreteroads.ca).

As illustrated in figure (4.17): 1) transportation is required from (A) processing of material to the manufacturing facility (B) and, 2) transportation from the manufacturing facility (B) to two different final distribution centers (C&D) and returning to the departure point B. All vectors represent the distances corresponding to 1 hour traveling.

Figure 4.17- Transportation flow for the manufacturing scenario.

For the manufacturing scenario several implications are involved regarding the transportation flow.

TRANSPORTATION MOVEMENT	PATH	PARTS	MATERIALS	(weight/WP weight)* MJ/H	Diesel (MJ)
From MP to MA	A h → B	All parts	AL-ST-PVC	(2027/2027)*1320 (h)	1320
From MA to Final Distribution	B h h D h C	Entire WP	AL-ST-PVC	(2027/2027)*1320 * 3(h)	3960
Total (MJ)					**5280**

Table 4.11 -Analysis of the existing relation between product weight and fuel efficiency for manufacturing.

The essential point to understand in this analysis (table 4.11) is the connection between product weight and the fuel efficiency. In simple terms, the idea is to show how gas mileage affects truck performance depending on the weight being transported. 1000 water pumps were chosen as the baseline quantity related to truck capacity. Since each water pump weigh 2.027 kg, 1000 units will represent a weigh of 2027 kg. For the truck used for this study, the amount of diesel required to travel for an hour is approximately 9 gallons of diesel, which can be translated in terms of energy to 1320 mega joules (MJ). This data was estimated by solving the following problem.

<u>Data:</u>

- 6.7 miles per gallon
  60 miles traveled per hour
- A gallon of diesel = 146.7 MJ (*Source:* Energy Information Administration) (http://www.eia.doe.gov/kids/energyfacts/science/unitsindex.html)

Accordingly, 60 m/h ÷ 6.7 m/g = 8.965 g/h which is about 9 gallons of diesel per hour. The energy content of a diesel gallon is equivalent to 139,000 BTU=146.7 MJ. Therefore, 146.7 MJ/g *9 g= 1320 MJ of diesel fuel.

Knowing that for transporting 1000 product units for an hour traveling cost about 1320 MJ of diesel input, the transportation analysis (in the remanufacturing scenario) goes according to the following movements.

	TRASNPORTATION MOVEMENT	PATH	PART	MATERIALS	(WEIGHT/ WP WEIGHT)* MJ/H	DIESEL (MJ) *
1	From Drop-off location to RMC		Water pump core	Al-ST-PVC	(2027/2027)*1320	1320
2	From RMC C to MA		Housing, shaft, pulley, impeller & bearing shaft	AL-ST	(2020/2027)*1320	1316
3	From RMC to RCC		Ball bearings, metal spring and metal ring	ST	(2/2027)*1320	1.30
4	From RCC to MA		Ball bearings, metal spring and metal ring	ST	(2/2027)*1320	1.30
5	From MP to MA		Bearing separators, ball bearing cover, and plastic ring.	PVC	(7/2027)*1320	4.56
6	From MA to Final Dist		Entire water pump	Al-ST-PVC	(2027/2027)*1320	3960
	Total		--------------------------	-----------	---------------------------	**6602 MJ**

Table 4.12 -Analysis of the existing relation between product weight and fuel efficiency for remanufacturing.

After understanding this flow, in the life cycle assessment diagram the route goes as follows:

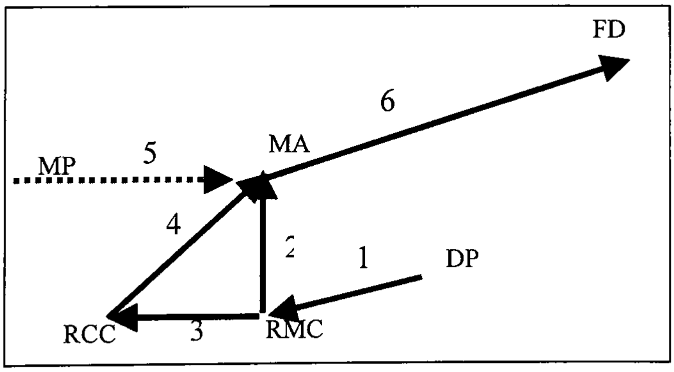


Fig 4.18- Transportation flow for the remanufacturing scenario.

The analysis shows that to produce 1000 water pumps is needed 5280 MJ of diesel, while 6602 MJ of diesel is required for the remanufacturing process (figure 4.18) of the same amount of water pumps (1000 units). As a result, it can be concluded that remanufacturing 1000 water pumps requires (6602/5280)=1.25 times the amount of energy in a manufacturing production systems.

4.8 Water Pump Manufacturing Analysis -Life Cycle Inventory

At this point, in the development of this research, all resources and releases resulting from the manufacturing and remanufacturing process of the materials contained in a water pump were explained. Then, the entire analysis comparing resources and emissions- and all appropriate manufacturing implications- is developed and presented. These materials inputs and outputs as well as the energy requirements for the entire water pump are compiled in the set of tables presented in the next pages. Also, carbon dioxide emissions associated with that energy are estimated using US emissions [8]factors. The inputs and outputs associated with the production and the remanufacturing of the product being evaluated are shown in the following section

After data compilation, LCA is conducted. Software results can be observed in chapter 5

4.8.1 To produce a water pump

1) **Energy Analysis to produce a WP**

1a- Energy Inputs to produce a WP

	Aluminum parts	Steel parts	PVC parts	Al+ST+PVC
Material Weight	**1.078kg**	**0.942kg**	**0.007kg**	**1.078 kg AL+0.942 ST + 0.007 PVC**
Coal (MJ)	65.3893	21.043	0.0761	86.509
Oil (MJ)	20.6908	3.8947	0.0145	24.600
Natural Gas (MJ)	47.8363	3.352	0.0150	51.203
Total (MJ)				**162.312**

Table 4.13- Energy consumption required for producing a water pump. (Source: Year 2000 Aluminum LCI Report for International Primary aluminum Institute- March 2003; The Steel Industry Report 2002; European Council if Vinyl Manufactureres- May 1993).

Table 4.13 shows the weight of each material in the WP and the energy consumption data per material. It shows that the total amount of energy- in terms of coal, oil and natural gas- among all materials correspond to 162.3 MJ

[8] Refer to appendix E to review US emissions factors to estimate carbon dioxide emissions.

1b- Outputs (CO2 emissions) from Energy Consumption

	Emission Factors	AL	CO2 (kg)	ST	CO2 (Kg)	PVC	CO2 (Kg)	Total kg of CO2/ Energy Consumption
Mat Weight		**1.078 kg**		**0.942 kg**		**0.007kg**		
	Kg CO2/kwh	**KWH**		**KWH**		**KWH**		
Coal	0.960	18.165	17.439	5.8457	5.612	0.02197	0.02110	23.072
Oil	0.870	5.748	5.001	1.0819	0.941	0.00403	0.00350	5.946
Natural Gas	0.597	13.289	7.933	0.9312	0.556	0.00417	0.00249	8.492
Total (kg)			**30.373**		**7.109**		**0.0271**	**37.509**

Table - 4.14 CO2 emissions associated with energy consumed to produce a water pump.

Table 4.14 indicates the total amount of CO2 emissions associated with energy consumption. The energy expressed in kwh is multiply by the appropriate emission factor for each one of the fuels. According to the results, the total amount of CO2 emissions resulting from energy consumption is 37.5 kg for a water pump that itself only weighs 2.041 kg.

2- Raw material acquisition for manufacturing a WP

Inputs
1.078 kg of Aluminum
0.942 kg of Steel
0.007 kg of PVC

Table 4.15- Raw material requirements for water pump.

3- Transportation from Materials Processing (PM) to Manufacturing and Assembly (MA)

h

A → **B**

Inputs	**Diesel**
Oil	1.325 MJ
Outputs	**Kg of emission / hour**
Carbon Monoxide	1.50E-03
Nitrogen Oxides	6.53E-03
Particulates Matters	1.90E-04
Sulphur Oxides	1.00E-04
VOC	1.90E-04

Table 4.16- Transportation inputs (energy) and outputs (emissions) to produce a water pump.

Table 4.16 shows the energy input (in terms of oil) for the transportation of materials. Also are shown the emission outputs related to the transportation from the PM facility to the MA location.

4- Materials Manufacturing Stage

4a- Energy Consumption

Material Weigt/ Inputs	1.078 kg of AL	0.942 kg of Steel	0.007 kg of PVC	Total
Hard Coal (MJ)	50.8676	13.4273	0.0698	64.3647
Oil (MJ)	11.0700	1.9999	0.0021	13.072
Natural Gas (MJ)	32.9092	1.8491	0.0138	34.772
Total (MJ)	**94.8468**	**17.2763**	**0.0857**	**112.2087**

Table 4.17- Energy inputs for the material manufacturing stage

Table 4.17 shows the energy consumption required per each one of the materials for its production processes. It should be noted that this energy is already included (numbers in red) in the analysis previously described in table 4.13 (energy inputs to produce an entire WP) but these inputs are shown again to maintain consistency in the analysis (inputs and outputs per stage.

4b- PVC Feedstock (energy to produce raw materials)

INPUTS TO PRODUCE 0.007 KG OF PVC	RAW MATERIAL (KG)
Hard Coal (kg)	0.00301
Oil (kg)	0.00763
Natural Gas (kg)	0.00914
Total (kg)	**0.0198**

Table 4.18- Feedstock requirements for producing 0.007 kg of PVC.

Table 4.18 shows the values corresponding to the feedstock (inputs) required in the PVC manufacturing process.

4c- Outputs of Material Manufacturing Stage for Aluminum Material

OUTPUTS	KG OF EMISSIONS GENERATED FROM PRODUCING 1.078 KG OF AL
Nitrogen Oxides	3.06E-03
Sulpur Oxides	2.66E-02
Mercury	2.16E-07
(w) Mercury	1.94E-06
Benzo(A)Pyrene	5.50E-03
CF4	2.37E-04
C2F6	2.26E-05
Hydrogen Chloride	7.22E-05

Table 4.19- Emissions associated with the production of 1.078 kg of aluminum. (Source: Year 2000 Aluminum LCI report for the International Aluminum Institute)

Table 4.19 shows the (air and water) emissions resulting from the manufacturing process of the aluminum.

4e- Outputs of Material Manufacturing Stage for the Steel Material

OUTPUTS	KG OF EMISSIONS FROM PRODUCING 0.942 KG OF STEEL
Carbon Monoxide	2.49E-02
Nitrogen Oxides	2.05E-03
Sulphur Oxides	2.06E-03
(w) Ammonia	9.42E-05
(w) Chromium	1.88E-05
(w) COD	1.77E-04
(w) Lead	1.21E-07
(w) Nickel	8.76E-08
(w) Nitrogen	4.63E-05
(w) Phenol	4.90E-06
(w) Phosphate	1.62E-06
(w) Phosphurus	6.34E-07

Table 4.20- Emissions (to air and water) associated with the production of 0.942 kg of steel (Source: The Steel Industry Report, 2002)

Table 4.20 shows the (air and water) emissions resulting from the steel manufacturing.

4f- Outputs of Material Manufacturing Stage for the PVC Material

OUTPUTS	KG OF EMISSION	KG OF EMISSION
	From producing 0.007 kg of PVC	Total + Petroleum Refining
Carbon Monoxide	1.75E-07	7.63E-06
Carbon Dioxide	4.53E-04	1.38E-02
Sulfur Oxides	3.64E-07	1.21E-04
Nitrogen Oxides	1.67E-06	8.25E-05
Hydrogen Sulfide	2.10E-08	2.10E-08
Methane	1.82E-06	1.08E-04
Lead	2.80E-09	2.80E-09
Mercury	4.90E-09	4.90E-09
Dichloroidoethane (HCI)	3.68E-07	3.68E-07
Ammonia	3.92E-07	3.92E-07
VCM	1.65E-06	1.65E-06
VOC	2.10E-08	2.10E-08
Ethylene	9.45E-08	9.45E-08
(w)COD	1.24E-05	1.25E-05
(w)BOD	1.87E-06	1.93E-06
(w) Phenol	8.40E-09	6.79E-08
(w) NA	7.06E-04	7.06E-04
(w) Iodomethane	1.28E-03	1.28E-03
(w) SO4	4.69E-05	4.69E-05
(w) Phosphate	4.31E-07	4.31E-07
(w) Arsenic	5.60E-09	5.60E-09
(w) VCM	2.73E-08	2.73E-08

Table 4.21- Emissions (air and water) associated with the production of 0.007 kg of PVC. (Source: European Council of Vinyl- May 1993)

Table 4.21 shows air and water emissions resulting from PVC manufacturing.

5- Product Fabrication stage

Process	Aluminum Die Casting	Welding	Injection Molding
Inputs	1.078 kg of AL	0.305 kg of Steel	0.007 kg of PVC
Hard Coal (MJ)	6.36E-02	8.085	8.99E-01
Oil (MJ)	7.21E-01	0.2448	2.72E-02
Natural Gas (MJ)	1.20E+01	1.5955	1.77E-01
Total	**1.28E+01**	**9.9253**	**1.10E+00**

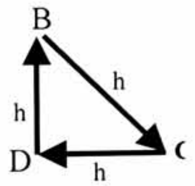
Table 4.22- Energy inputs for the manufacturing processes experienced by WP materials.

Table 4.22 shows the energy inputs involved in the processing of materials corresponding to the energy expenditure for: Die Casting process for aluminum material; the Welding process that the steel has to experience and the Injection Molding process to shape the PVC. It should be noted that the amount of material processed corresponds to the weight that the materials represent in the WP. (Numbers in red indicated that energy is already included in the energy analysis shown for the entire WP in table 4.13)

6- Packaging (no inputs/ no outputs)

Given the fact that there are not emissions resulting from the packaging process of a water pump, inputs and outputs were not included in this analysis.

7- Transportation Final Product Distribution



INPUTS	DIESEL
Oil (MJ)	3.98E+00
Outputs	**Kg of emission/ (3) hours**
Carbon Monoxide	4.50E-03
Nitrogen Oxides	1.96E-02
Particulates Matters	5.70E-04
Sulphur Oxides	3.00E-04
VOC	5.70E-04

Table 4.23- Inputs and outputs corresponding to the final product transportation. (B is the starting point).

The final product distribution requires the transportation flow presented in the figure 4.13. Table 4.23 shows the air emissions associated with these transportation movements.

4.8.2 To remanufacture a Water Pump

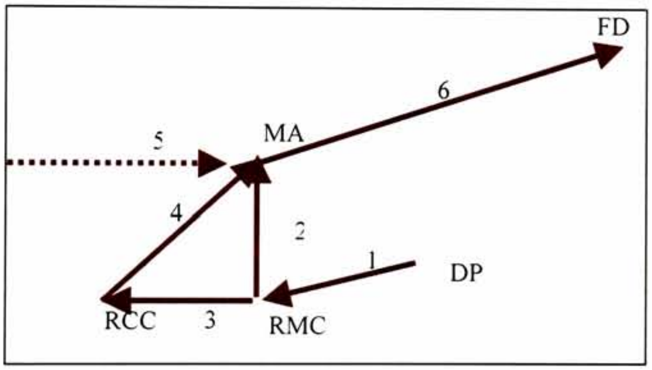
Different from the previous analysis this part of the evaluation includes the remanufacturing data and the recycling data that is required in the remanufacturing process of a water pump.

1) Transportation (Energy Inputs)

	Energy Consumption for Transportation	(MJ)
1	From drop-off collection to RMC	1.32E+00
2	From RMC to RCC (for steel)	1.30E-03
3	From RCC to RMC (for steel)	1.30E-03
4	From RMC to Manufacturing & Assembly (St +AL)	1.32E+00
5	From MP to MA (for PVC)	4.56E-03
6	From final product distribution (all materials)	3.96E+00
	Total Transportation	**6.60E+00**

Table 4.24- Energy required for transportation when remanufacturing a WP.

(Figure 4.16)



Refer to figure 4.16 to understand the transportation movements shown in table 4.24.

1b) Transportation (Emissions Outputs)

TRANSPORTATION /EMISSIONS (KG)	FROM DP TO RMC	FROM RMC TO RCC	FROM RCC TO RMC	FROM RMC TO MA	FROM MP TO MA	FINAL DIS	TOTAL EMISSIONS (KG)
Carbon Monoxide (kg)	1.50E-03	1.47E-06	1.47E-06	1.49E-03	5.17E-06	4.50E-03	**7.50E-03**
Nitrogen Oxides (kg)	6.53E-03	6.41E-06	6.41E-06	6.51E-03	2.25E-05	1.96E-02	**3.27E-02**
Particulates Matters (kg)	1.90E-04	1.86E-07	1.86E-07	1.89E-04	6.55E-07	5.70E-04	**9.50E-04**
Sulphur Oxides (kg)	1.00E-04	9.81E-08	9.81E-08	9.96E-05	3.45E-07	3.00E-04	**5.00E-04**
VOC (kg)	1.90E-04	1.86E-07	1.86E-07	1.89E-04	6.55E-07	5.70E-04	**9.50E-04**

Table 4. 25- Air emissions associated with the transportation energy required for remanufacturing a WP

Table 4.25 refers to the chemical emissions resulting from the energy required for transportation. The table shows the amount of chemicals released to air during the transportation of materials.

1c- Transportation Outputs (CO2 emissions)

ENERGY FOR TRANSP (MJ)	KWH	EMISSION FACTOR (OIL)	KG OF CO2
6.63	1.841814	0.87	1.602

Table 4.26-Kg of CO2 emissions associated with energy requirements for transportation for remanufacturing.

Table 4.26 shows the CO2 emissions resulting from transportation. Emission factor for Oil fuel has been used to estimated this type of emissions.

2- Materials Remanufacturing (Energy Inputs)

Inputs	Aluminum Remanufacturing	Steel Recycling	Steel Remanufacturing	PVC production	Total = Rem+Rec+Pro (MJ)
Material weight	**1.078 kg**	**0.022 kg**	**0.92 kg**	**0.007 kg**	
Coal (MJ)	0.507	0.0453	0.462466	0.0761	1.0906
Oil (MJ)	0.015	0.0579	0.014308	0.0145	0.1017
Natural Gas (MJ)	0.125	0.0600	0.093305	0.0150	0.2934
Total (MJ)					**1.4858**

Table 4.27- Energy consumption for remanufacturing a WP.

Table 4.27 presents the energy requirements to remanufacture the housing aluminum and the steel parts that can be reconditioned. Also, shown is the energy associated with the production of 0.007 kg of PVC. The energy consumption registered for the WP remanufacturing activities is much less than the energy required in the manufacturing scenario. That is because aluminum and steel parts do not need to be re-produced.

2b- Materials Remanufacturing (Outputs from energy consumption)

Outputs	Emission Factors	AL Rem (kwh)	CO2 E (kg)	Steel RC (kwh)	CO2 E (kg)	Steel Rem (kwh)	CO2 E (kg)	PCV (kwh)	CO2 E (kg)	Total Emissions (kg)
Coal	0.960	0.141	**0.135**	0.0126	**0.012**	0.12847	**0.1233**	0.021141	**0.0203**	0.291
Oil	0.870	0.004	**0.004**	0.0161	**0.014**	0.00397	**0.0035**	0.004028	**0.0035**	0.025
Natural Gas	0.597	0.035	**0.021**	0.0167	**0.010**	0.02592	**0.0155**	0.004167	**0.0025**	0.049
Total CO2 (kg)			**0.160**		**0.036**		**0.142**		0.0263	**0.3643**

Table 4.28- CO2 emissions associated with the energy required for remanufacturing a water pump.

Table 4.28 shows the CO2 emissions resulting from the aluminum and steel remanufacturing operations. Also, is sown the CO2 emissions resulting for the energy required to reproduce 0.007 kg of PVC material. The total amount of CO2 emissions resulting from remanufacturing activities is 0.36 kg.

- Energy consumption and CO_2 emissions summary for remanufacturing.

Remanufacturing	Emissions Kg of CO2	Energy for Remanufacturing (MJ)
Transportation	1.6024	6.63
Reprocessing	0.365	1.4858
Total	**1.9674**	**8.1158**

Table 4.29- Total energy and emission arising when remanufacturing a water pump.

The table 4.29 shows that the total energy needed to remanufacture the WP accounts for only 8.11 (MJ). This amount of energy is approximately 20 times less than the energy consumed in the manufacturing scenario. For CO_2 emissions, the total accounts for about 2 kg of CO_2, which is 18 times less emissions than in the manufacturing setting.

2c- PVC Feedstock (energy to produce raw materials)

INPUTS	RAW MATERIAL KG
Hard Coal (kg)	0.00301
Oil (kg)	0.00756
Natural Gas (kg)	0.00913
Total	**0.0198**

Table 4.30- Feedstock requirements for producing 0.007 kg of PVC.

Since the PVC needs to be reproduced when remanufacturing the WP, table 4.30 presents the same values as in the manufacturing production setting.

3- Material Outputs from Remanufacturing operations.

3a-Outputs from steel recycling

Outputs	From 0.022 Steel Recycling
Carbon Monoxide	5.21E-05
Nitrogen Oxides	3.37E-05
Sulphur Oxides	4.36E-05
(w) Ammonia	1.73E-08
(w) Chromium	5.94E-10
(w) COD	6.91E-07
(w) Lead	2.02E-09
(w) Nickel	1.50E-09
(w) Nitrogen	2.49E-08
(w) Phenol	6.78E-10
(w) Phosphate	6.78E-08
(w) Phosphorus	1.43E-06

Table 4.31- Emissions (to air and water) associated to steel recycling operations.

Table 4.31 shows the chemical emissions released to air and water resulting from the recycling operations involved in the remanufacturing process of a water pump.

3b-outputs from PVC production

PVC Production	From producing 0.007 kg of PVC	Total + Petroleum R
Carbon Monoxide	1.75E-07	7.63E-06
Carbon Dioxide	4.53E-04	1.38E-02
Sulfur Oxides	3.64E-07	1.21E-04
Nitrogen Oxides	1.67E-06	8.25E-05
Hydrogen Sulfide	2.10E-08	2.10E-08
Methane	1.82E-06	1.08E-04
Lead	2.80E-09	2.80E-09
Mercury	4.90E-09	4.90E-09
Dichloroidoethane (HCI)	3.68E-07	3.68E-07
Ammonia	3.92E-07	3.92E-07
VCM	1.65E-06	1.65E-06
VOC	2.10E-08	2.10E-08
Ethylene	9.45E-08	9.45E-08
(w)COD	1.24E-05	1.25E-05
(w)BOD	1.87E-06	1.93E-06
(w) Phenol	8.40E-09	6.79E-08
(w) NA	7.06E-04	7.06E-04
(w) Iodomethane	1.28E-03	1.28E-03
(w) SO4	4.69E-05	4.69E-05
(w) Phosphate	4.31E-07	4.31E-07
(w) Arsenic	5.60E-09	5.60E-09
(w) VCM	2.73E-08	2.73E-08

Table 4.32- Emissions (air and water) associated with the production of 0.007 kg of PVC

Table 4.32 shows the chemical emissions released to air and water resulting from PVC manufacturing. (In the remanufacturing scenario PVC needs to be reproduce)

4- Product Fabrication

4a- Injection molding

Inputs	For processing 0.007 kg of PVC by Injection Molding
Hard Coal (MJ)	8.99E-01
Oil (MJ)	2.72E-02
Natural Gas (MJ)	1.77E-01
Total (MJ)	**1.10E+00**

Table 4.33- Energy inputs for PVC injection molding process.

Table 4.33 shows the energy required to process the PVC material through the injection molding process. Different from the manufacturing scenario **Die Casting** process for aluminum material and **Welding** process for steel material are not required. These manufacturing activities are not require in the remanufacturing process of a WP.

5- Packaging (no inputs/ no outputs)

Given the fact that there are not emissions resulting from the packaging process of a water pump, inputs and outputs were not included in this analysis.

6- Final Transportation presented at the beginning along with other transportation flow for remanufacturing.

Having presented - stage by stage and process by process- all the data (inputs and outputs) associated with the manufacturing and remanufacturing process to produce an automotive water pump, the next step is to utilize TRACI to conduct the life cycle assessment. Subsequently, the data is entered into TRACI for both production setting – manufacturing and remanufacturing - and the software tool performs the appropriate calculations. After running the calculations the results are presented in the next chapter of this paper.

5- LCA RESULTS

In order to acquire an appropriate understanding of LCA results, it is necessary to have certain knowledge regarding the implications (cause-consequence) involved in each one of the categories evaluated by TRACI. In the background section of this paper (chapter 2), an explanation is provided describing what are the chemical contributors and the range of consequences that may result when any of these environmental categories is impacted.

LCA results are presented by category, first for manufacturing and then for remanufacturing scenarios. Afterwards, a comparison is made between both production alternatives to identify which choice provides a better solution to address environmental concerns. Before presenting TRACI results it is essential to have an understanding of the units in each categories. Methodologies for each impact category contained in TRACI convert chemical emissions and ecological stressors into significant measure units that quantify the magnitude of environmental impacts. The measure units are expressed in terms of "Equivalency Potential Factors". These factors indicate the potential of each chemical to impact environmental categories in comparison to the reference chemical used. For instance, for global warming impact category, the potential indicator is **CO2 equivalents/kg emission**, which means that certain amount of CO2 units are affecting the global warming category per each kg of emissions released to the environment.

-LCA results

Environmental Category	Equivalency Potential Indicator (E)	Units
Acidification	2.73E+00	H + moles equivalent/kg of emission
Ecotoxicity	1.26E+00	2,4-D equivalents/ kg emission
Eutrophication	1.45E-03	Nitrogen equivalents/ kg of emission
Fossil Fuel	1.20E+01	MJ surplus energy/MJ of extracted energy
Global Warming	3.90E+01	CO2 equivalents/kg of emission
Human Health Cancer	9.08E+00	Benzene equivalents/kg of emission
Human Health Criteria	1.56E-06	DALYs/tonne emission
Human Health Non-cancer	4.10E+01	Toluene equivalent/kg of emission
Photochemical Smog	6.67E-02	G NOx equivalents/ kg of emission
Water Use	3.23E+00	L / kg of processed material

Table 5.1- LCA results per category for the Manufacturing Scenario– Units (1 water Pump)

Table 5.1 presents the LCA presents result by category. The potential indicator **(E)** refers to the amount of equivalent units that are affecting each one of the categories.

If the number is close to 0 it means that it represents less impact to the environment. However, if the trend shows that the number is going away from 0, the categories are being affected with major intensity. Since each category addressees a different ecological problem and different characterization factors are used to calculate chemical impacts on the environment, there is no point in making any kind of comparison among them. Therefore, simply by observing the previous graphic, it cannot be concluded that the Global Warming category (39.0 E) is being more affected than the Acidification one (2.73 **E**). That is because their units suggest a different approach and hence, a different interpretation is required.

-LCA result

Environmental Category	Equivalency Potential Factor (E)	Units
Acidification	1.35E+00	H + moles equivalent/kg of emission
Ecotoxicity	1.18E-03	2,4-D equivalents/ kg emission
Eutrophication	1.47E-03	Nitrogen equivalents/ kg of emission
Fossil Fuel	1.43E-01	MJ surplus energy/MJ of extracted energy
Global Warming	1.98E+00	CO2 equivalents/kg of emission
Human Health Cancer	1.27E-01	Benzene equivalents/kg of emission
Human Health Criteria	1.52E-07	DALYs/tonne emission
Human Health Non-cancer	9.96E-02	Toluene equivalent/kg of emission
Photochemical Smog	3.29E-02	G NOx equivalents/ kg of emission
Water Use	1.50E+00	L / kg of processed material

Table 5.2- LCA results per category for the Remanufacturing Scenario– Units (1 water pump)

MJ surplus energy/MJ of extracted energy

Table 5.2 illustrates the set of results obtained from the LCA in the remanufacturing scenario. For this production alternative potential indicators are significantly less than in the manufacturing production alternative. Those is because primary processes for aluminum and for steel material are avoided, resulting in less energy consumption and emissions to air and water. To some level, these results are totally reasonable because the amount of energy requirements and chemical releases are much less than in the manufacturing setting.

In practice, the same product can be remanufacture more than once- that is when the real value of the remanufacturing option can be achieved- depending of how many life cycles can be added to the given product by incorporating the remanufacturing alternative.

Certainly, the number of life cycles can vary depending on several factors including cause of damage, part properties, part resistance to chemical treatment and the actual condition of the core when received. According to information provided by an expert source in the water pump remanufacturing business, an automotive water pump can be remanufacture on average 5 times. Some critical points regarding repairs are housing corrosion and bearing press fit that can generate costs, and as a consequence this economic-factor might change the number of remanufacturable life cycles per unit. Having this valuable information from industry and trying to illustrate the real value of remanufacturing, a practical model is simulated with the purpose of understanding the remanufacturing trends taking place in practice.

The model is intended to determine any difference regarding environmental impacts in the following settings. 1) Manufacturing 6 units and 2) Manufacturing 1 unit and subsequently remanufacturing the same unit 5 times to have the same number of usage cycles in both production scenarios. These numbers were selected based on the information that on average WP can be remanufactured 5 times.

LCA-Model / 6 Uses Vs 6 Uses

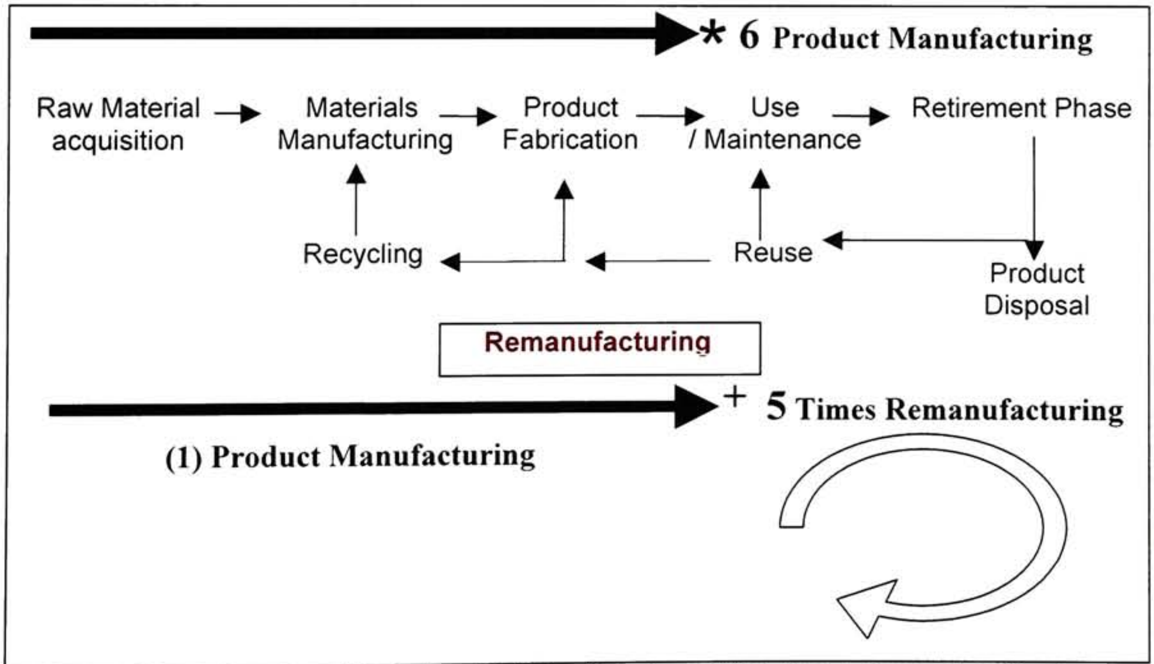


Figure 5.1 – Manufacturing a WP 6 times **Vs** (Manufacturing a WP 1 time + Remanufacturing the same unit 5 times).

Next results correspond to an analysis where the water pump is produced in different scenarios following the proposed LCA model.

Prod alternative Env/ Category	6 Man	1 Man + 5 Rem	% Of Improvement	Units
Acidification	1.64E+01	9.47E+00	42.19	H + moles equivalents
Ecotoxicity	7.58E+00	1.27E+00	83.26	2,4-D equivalents
Eutrophication	8.70E-03	8.78E-03	-0.92	Nitrogen equivalents
Fossil Fuel	7.23E+01	1.28E+01	82.34	MJ surplus
Global Warming	2.34E+02	4.89E+01	79.11	CO2 equivalents
Human Health Cancer	5.45E+01	9.72E+00	82.17	Benzene equivalents
Human Health Criteria	9.38E-06	2.32E-06	75.23	DALYs equivalents
Human Health Non-cancer	2.46E+02	4.15E+01	83.13	Toluene equivalents
Photochemical Smog	4.00E-01	2.31E-01	42.24	Nox equivalents
Water Use	1.94E+01	1.07E+01	44.63	L

Table 5.3- LCA for Manufacturing Vs Remanufacturing – Units (6 man Vs 1 Man + 5 Rem)

According to table 5.3 and taking into consideration the assumptions made through the length of the study, the results reflect that for the environmental categories evaluated by the software, only one shows a detrimental impact on the ecology. Ozone Depletion category resulted completely unaffected by either water pumps process. Nine of ten-(9/10)- categories reflect a significant benefit when using the remanufacturing approach as a production alternative. However, there is an exception in this trend for the Eutrophication category because the outcome shows some disadvantages of the remanufacturing option. In this case study, the results are showing that for the Eutrophication category, remanufacturing *does not represent a better production option in environmental terms*. Specifically for Eutrophication, the only category that presents a different behavior compared to others, the potential reason for this discrepancy is the amount of transportation involved in the remanufacturing setting. The Eutrophication chemical contributors are carbon, nitrogen and phosphate, and precisely two of these three chemical stressors- carbon and nitrogen- are released during transportation. Therefore, there is a logical connection that explains why Eutrophication is affected the most in the remanufacturing scenario.

Since processes of different nature such as recycling and remanufacturing do not necessarily occur in the same facility, some kind of transportation is required among facilities. As presented in the case study evaluation, the remanufacturing alternative involved additional transportation for the core and the defectives parts contained in the water pump.

Major improvements and benefits of the remanufacturing strategy are registered in the Ecotoxity category for (83.26%), followed by the Human Health Non-cancer category which counts for (83.13%), Fossil Fuel with (82.34%) and Human Health Cancer with (82.17%). Global Warming reflects (79.11%) of improvement and Human Health Criteria a (75.23%). The categories presenting less improvement are Acidification for (42.19%), and Photochemical Smog for (42.24%). Water consumption resulted to be less in the remanufacturing environment accounting for almost 45% of improvement when remanufacturing.

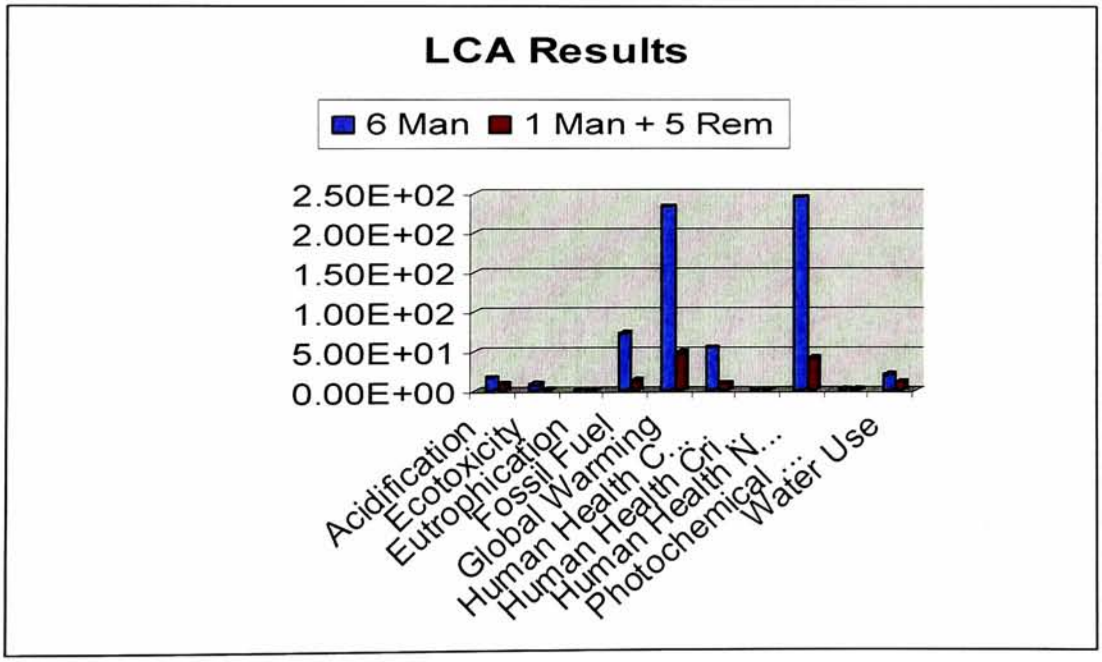


Figure5.2- TRACI LCA results for Manufacturing Vs Remanufacturing

Figure 5.2 illustrates the impacts obtained for each categories for both production scenarios. By observing the behavior in this graphic, it seems reasonable to suggest that remanufacturing is a better production alternative in environmental terms.

The software results offer the equivalent units by which each category is affected. However, to date, it is not known the weight that these "Potential Equivalency Factors" - **(E)** units- represent into each individual impact category. In other words, it cannot be resolved what are the possible damages related to the environmental impacts quantified by the software results for every environmental category.

Even though my analysis was based on a small numbers of water pumps, the LCA results and the improvement percentages obtained in this study will apply to a large amount of water pumps being evaluated as long as they follow the LCA model proposed in this study.

6. CONCLUSIONS AND FUTURE RESEARCH RECOMMENDATIOSN

6.1 Conclusions

The remanufacturing industry has been widely recognized for its economic benefits, but only a few decades ago manufacturers started becoming aware of the environmental gains that the remanufacturing industry can provide. The objective of this study was to identify and quantify environmental benefits and liabilities resulting from the remanufacturing process itself by taking into account the entire life cycle of a product. In this study an automotive water pump was used as the test vehicle to perform the analysis. Based on industry data, a LCA model was developed to compare environmental impacts resulting from different manufacturing scenarios. An extensive LCI inventory of the water pump materials was gathered to perform the LCA. The results obtained were to be used to recommend production practices that minimize the magnitude of ecological impacts affecting our environment.

This study has supported the statement made by remanufacturing precursors, concerning the fact that remanufacturing involves less raw material requirements, which can be translated in energy savings through the production process. These energy savings represent one of the major benefits that the remanufacturing industry can provide. Certainly, for the water pump analysis, the energy required in the remanufacturing scenario is approximately 20 times less than in the manufacturing setting. The values correspond to 162.3 MJ and 8.12 MJ respectively. Consequently, CO2 emissions resulting from energy consumption also present the same trend.

The results obtained suggest that remanufacturing represents a superior alternative in ecological terms when compared to manufacturing. Although this study's results are fairly case specific, they demonstrate that by adding life cycles to products suited for remanufacturability, the contributors and chemical stressors responsible for negative environmental impact are significantly reduced.

Eleven environmental categories were utilized as the conclusion parameters to determine which production alternative, between manufacturing and remanufacturing, provoke less detrimental impacts on the environment. LCA results show that Ozone Depletion category resulted totally unaffected by either production alternative. Nine categories registered environmental benefits from remanufacturing while Eutrophication was the only environmental category negatively impacted in the remanufacturing scenario mainly because additional transportation requirements. During the product analysis it was observed that remanufacturing systems require extra transportation having a negative impact on the environment. But depending on the re-capture strategies that companies apply to reclaim their product, transportation flows will vary affecting the environment positively or negatively depending on how good the logistic of transportation is designed.

Higher benefits were observed in categories related to human quality- Human cancer and Human non-cancer- by incorporating remanufacturing into the typical LCA. The potential reason for this gain is that the release of many chemicals and carcinogens are avoided in remanufacturing because some materials only need to be reconditioned rather than reproduced. Given that remanufacturing environment is characterized mostly for the presence of numerous cleaning technologies for material treatment, it might be reasonable to believe that water consumption requirements for this production setting are higher than for manufacturing systems. However, according to the obtained results and contrary to common belief, remanufacturing processes do not necessarily require more water consumption than manufacturing. Water requirements will vary depending on material properties and also on the cleaning technologies apply for reconditioning processes. In addition, the water used for the production of materials is avoided in the remanufacturing scenario.

All these positive factors encountered in the remanufacturing setting might lead to the conclusion that remanufacturing can contribute to increasing the eco-efficiency of production systems.

6.2 Recommendations For Future Research.

The areas that provide opportunities for major improvements and further research are software constraints and LCA interpretations. A major software limitation is the evaluation of the product/process energy consumption in terms of fossil fuels. This restriction forces LCA practitioners to exclude other energy sources relevant for obtaining an accurate energy analysis. Future versions of the TRACI software should include the possibility of inputting other types of energy such as electricity. Also, more extensive and scientific analysis can be done regarding TRACI methodologies to reincorporate the two environmental categories- water use and land use- that were removed in the latest version of the software package.

It is necessary the development of supporting information to formulate stronger interpretations of LCA results. Although the software tool is capable of quantifying environmental impacts, there is a lack of conclusive information available to determine a relationship between the software results and the magnitude of the environmental damages imply by those results. In addition, more work can be done by establishing confidence intervals regarding the range of damages that chemical emissions can provoke. Therefore, the midpoint level approach utilized by TRACI to estimate environmental impacts can be better defined by matching chemical harm and potential environmental effects.

The evaluation of other environmental categories can be included in future version of the TRACI software. Biodiversity might be a good category to be analyzed, opening the possibility to study unusual trends observed in plants and animals as a result of ecological impacts. In addition, future research can focus into evaluating how to improve remanufacturing systems that require in an extensive amount of transportation to reduce the magnitude of negative impacts that they are provoking on the environment.

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8. APPENDICES

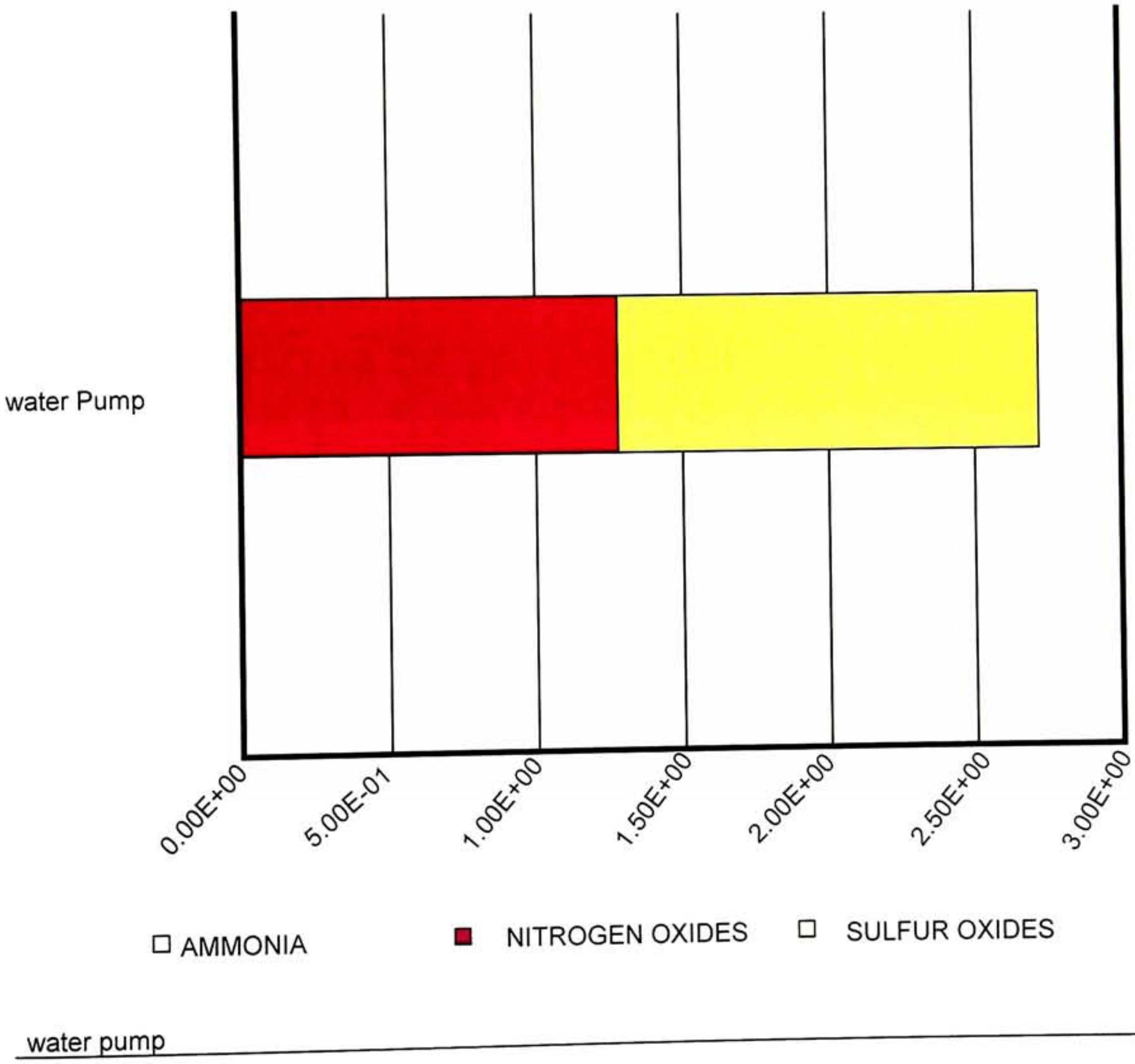
Appendix A- TRACI Results for Manufacturing & Remanufacturing

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for manufacturing

Impact Type: Acidification

Equivalency Potential Indicator: moles H + -e



water pump

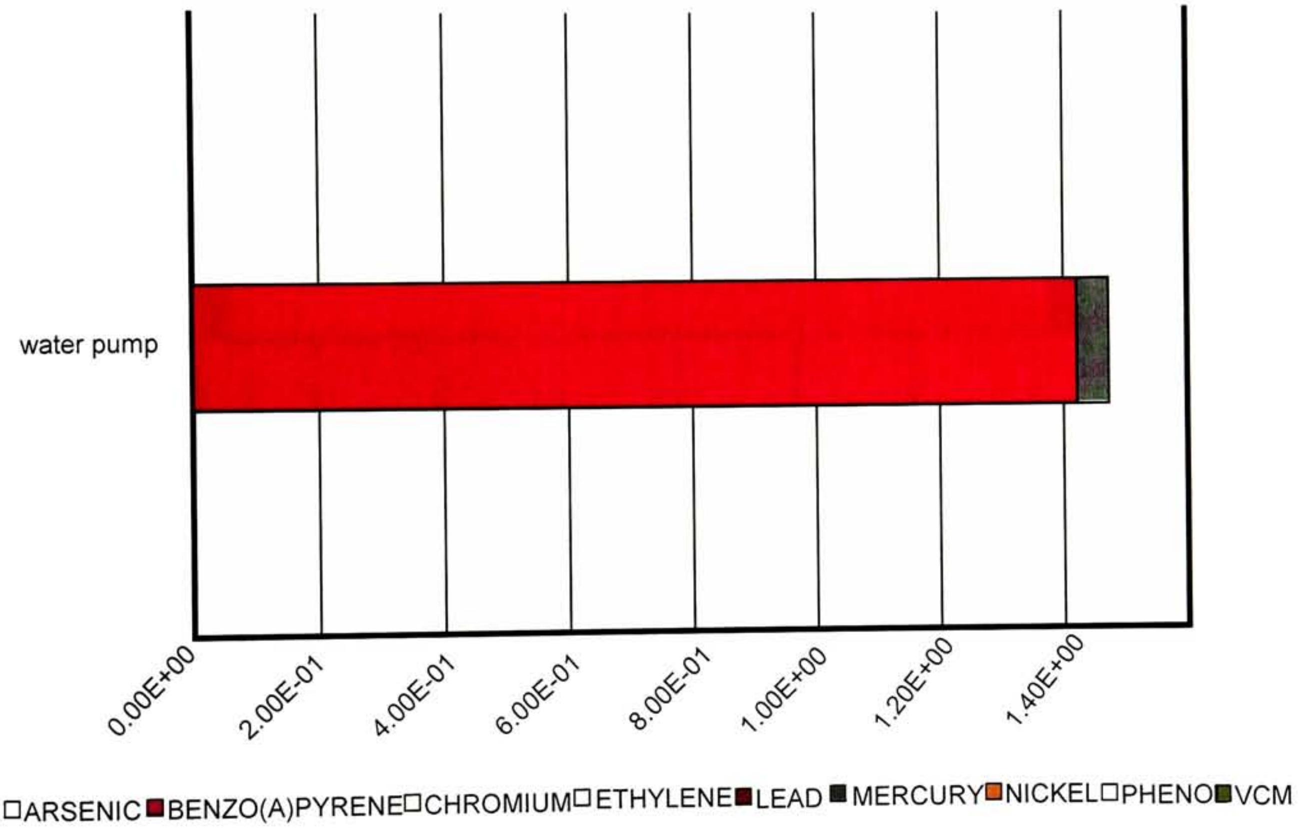
Resource/Release	Characterization Result
AMMONIA	8.90E-05
NITROGEN OXIDES	1.25E+00
SULFUR OXIDES (SOX)	1.48E+00

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for manufacturing

Impact Type: Ecotoxicity

Equivalency Potential Indicator: Kg 2,4-D-e



Water pump

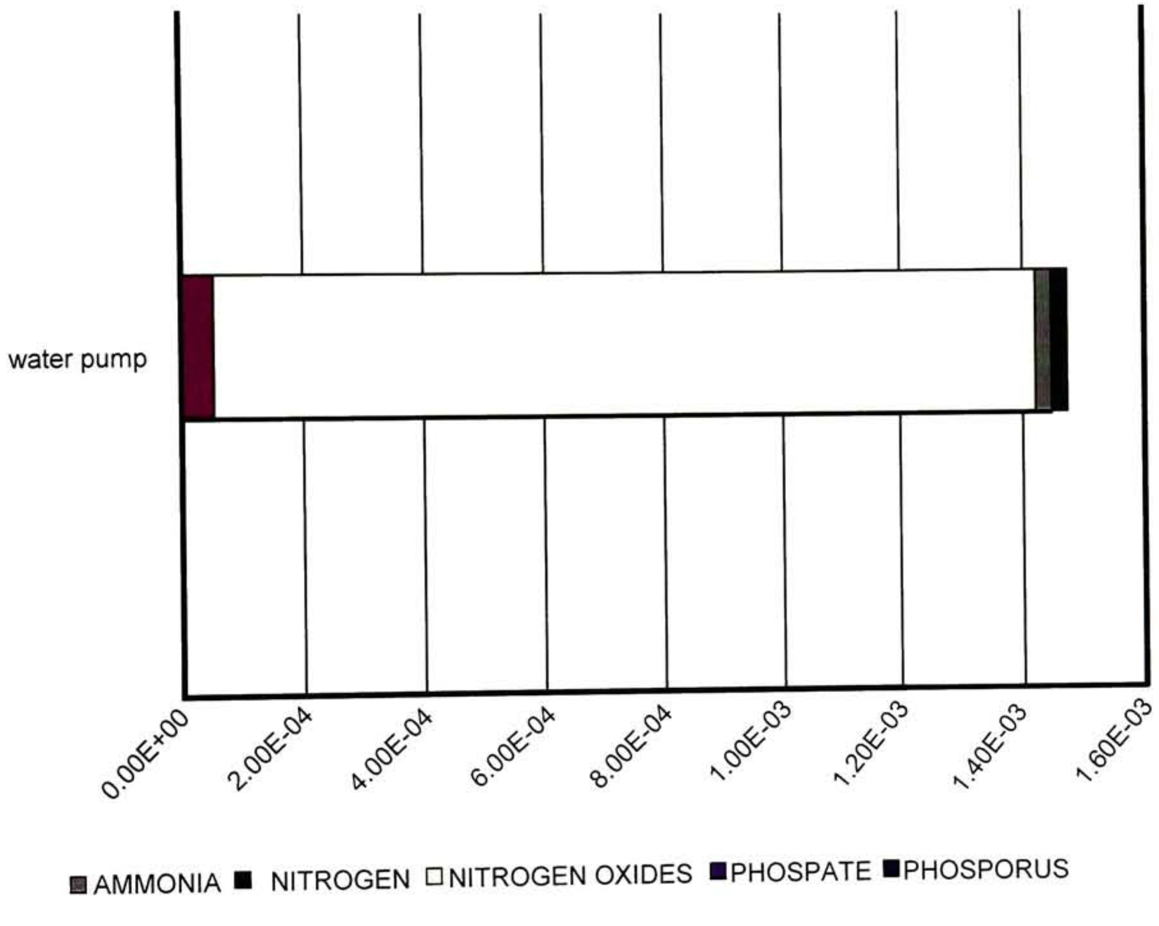
Resource/Release	Characterization Result
ARSENIC	1.28E-08
BENZO(A) PYRENE	1.21E+00
CHROMIUM	9.78E-06
ETHYLENE	7.28E-12
LEAD	9.48E-08
MERCURY	5.32E-02
NICKEL	1.14E-05
PHENOL	4.62E-06
VCM	3.55E-10

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for manufacturing

Impact Type: Eutrophication

Equivalency Potential Indicator: Kg N-e



Water pump

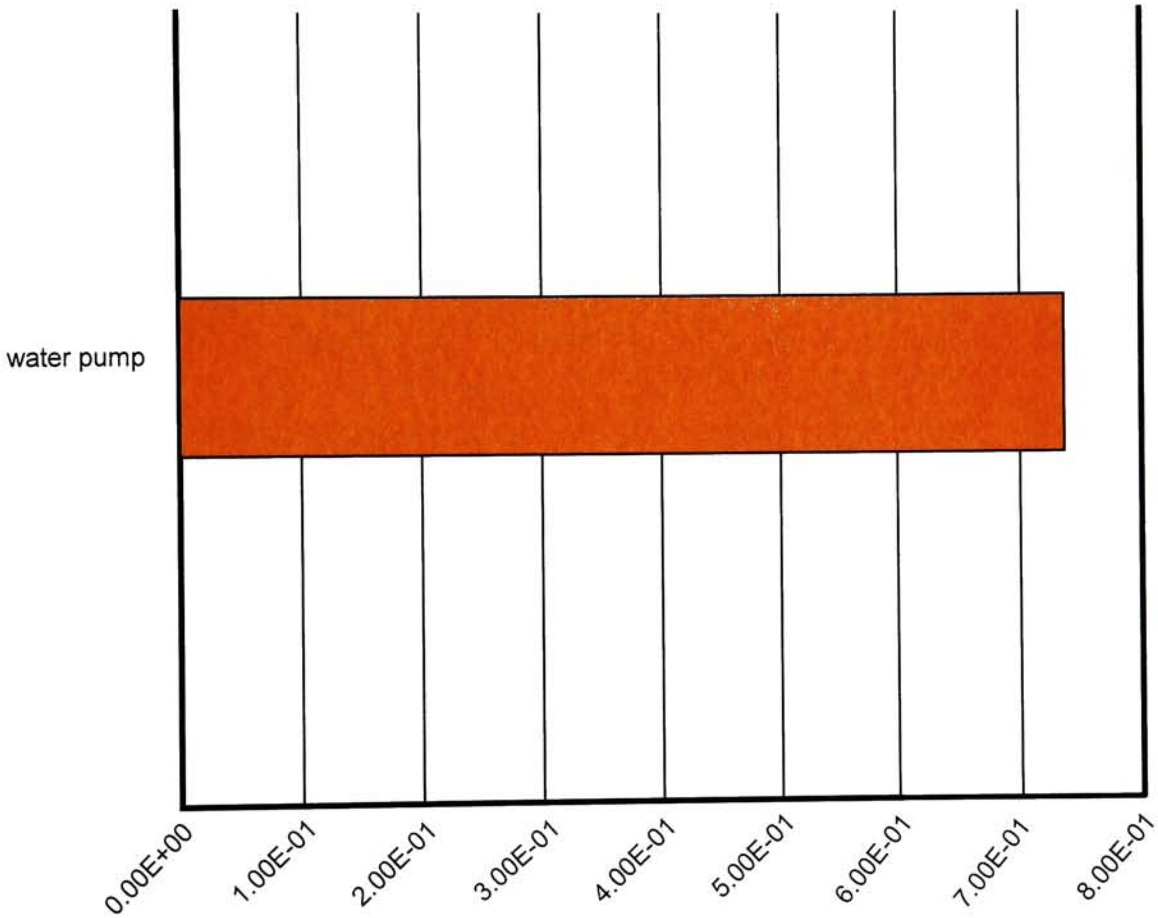
Resource/Release	Characterization Result
AMMONIA	1.11E-07
NITROGEN	4.57E-05
NITROGEN OXIDES	1.39E-03
PHOSPHATE	1.03E-05
PHOSPHORUS	4.62E-06

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for manufacturing

Impact Type: Fossil Fuel Hard Coal

Equivalency Potential Indicator: MJ surplus



Water pump

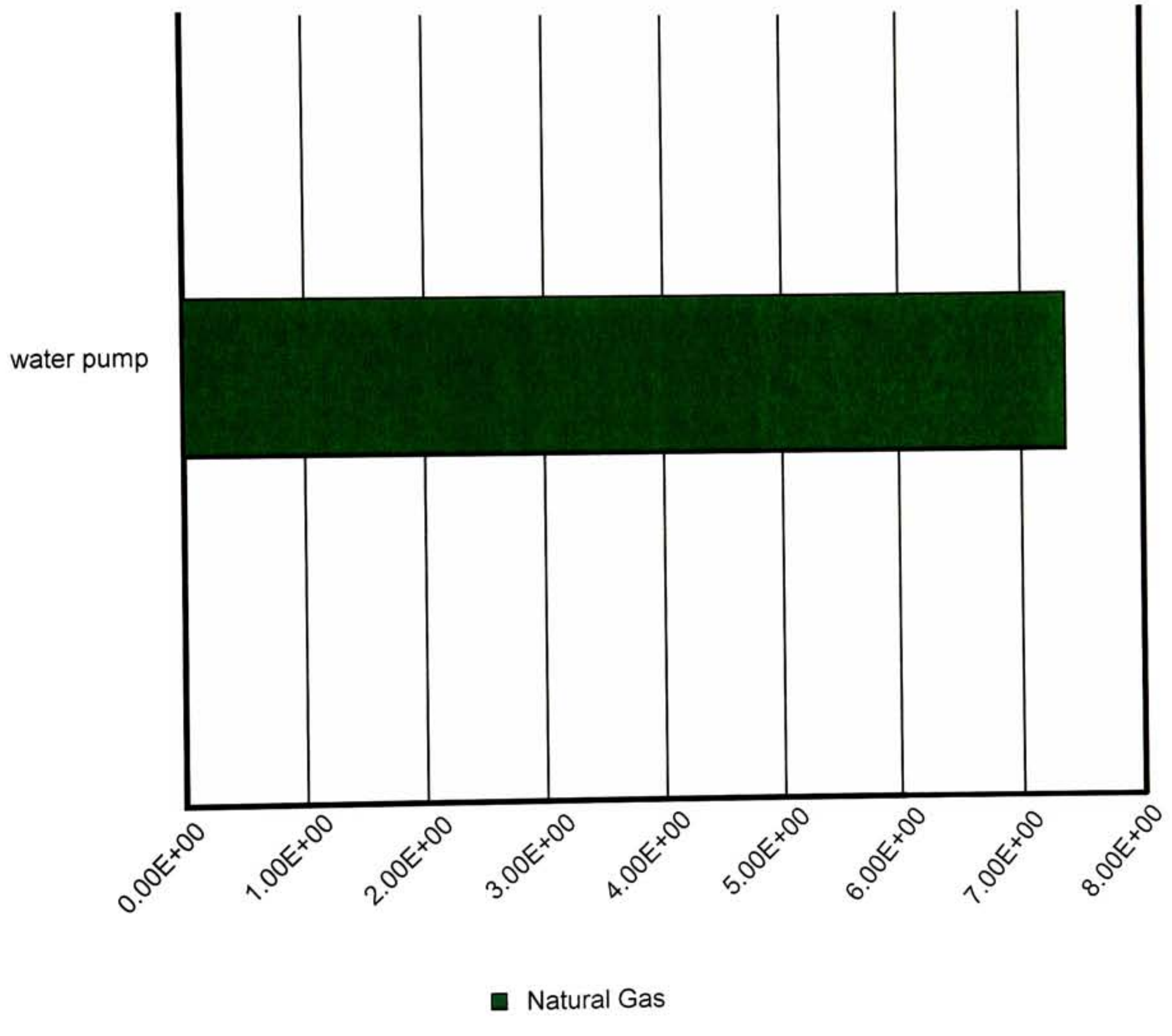
Resource/Release	Characterization Result
COAL	7.44E-01

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for manufacturing

Impact Type: Fossil Fuel Natural Gas

Equivalency Potential Indicator: MJ surplus



Water pump

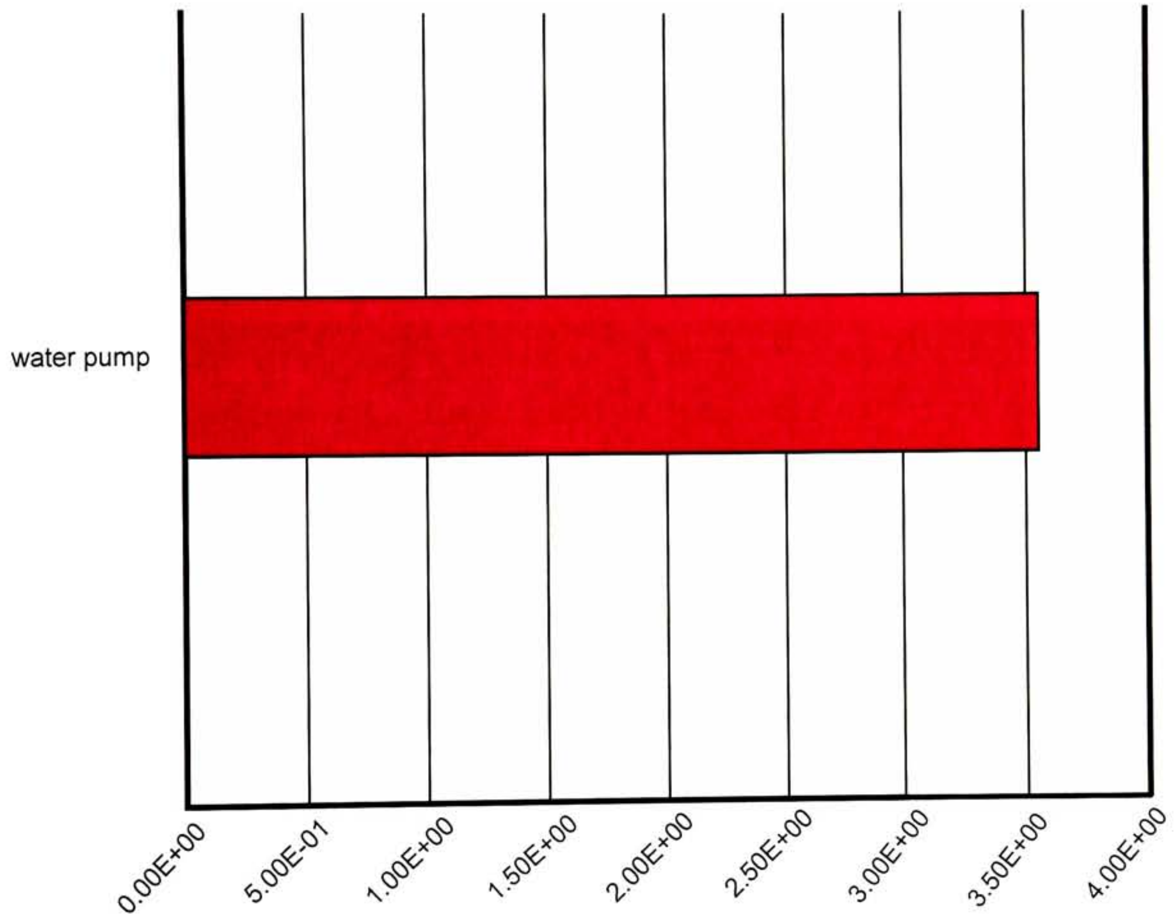
Resource/Release	Characterization Result
NATURAL GAS	7.72E+00

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for manufacturing

Impact Type: Fossil Fuel Oil

Equivalency Potential Indicator: MJ surplus



Water pump

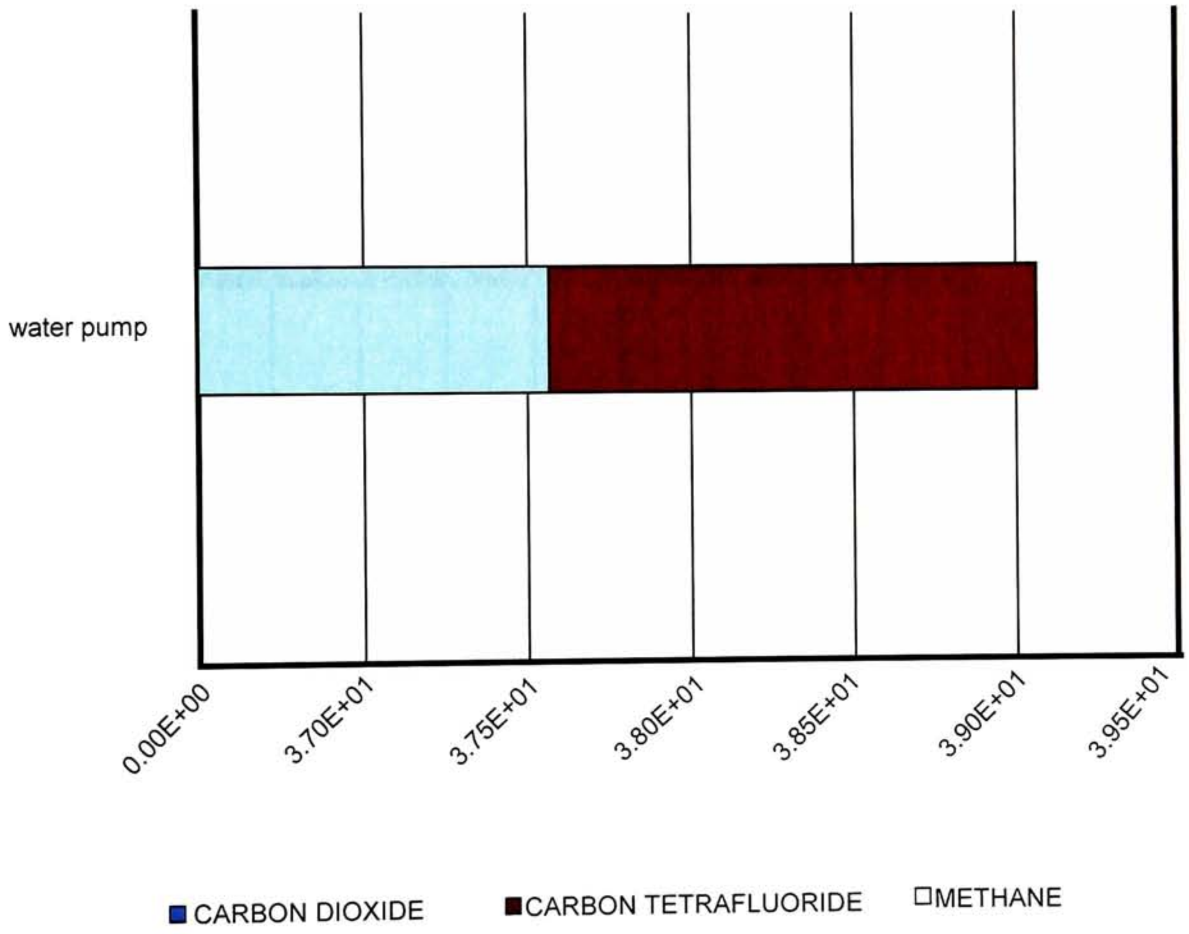
Resource/Release	Characterization Result
OIL	3.58E+00

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for manufacturing

Impact Type: Global Warming

Equivalency Potential Indicator: Kg CO2-e



Water pump

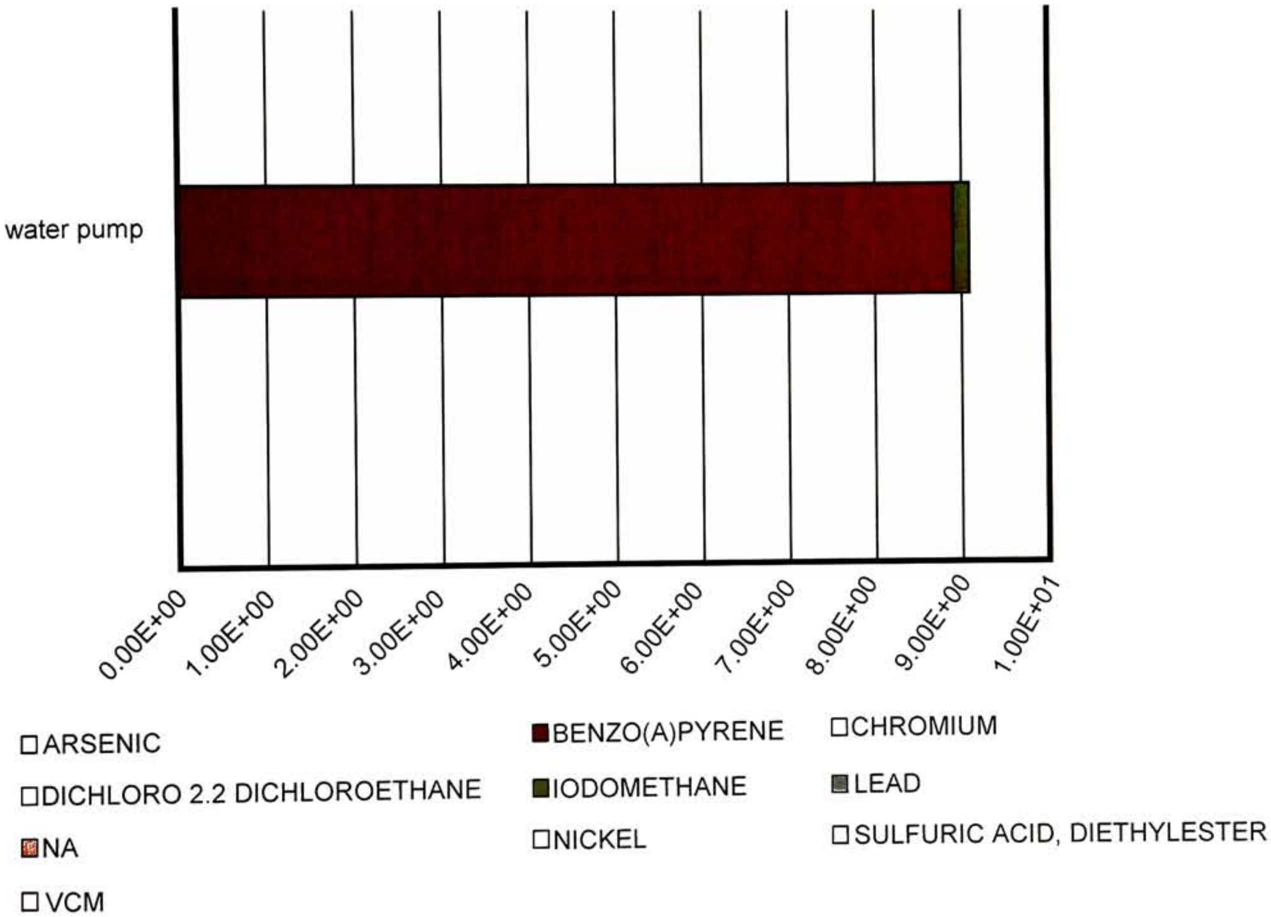
Resource/Release	Characterization Result
CARBON DIOXIDE	3.75E+01
CARBON TETRAFLUORIDE	1.54E+00
METHANE	2.27E-03

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for manufacturing

Impact Type: Human Health Cancer

Equivalency Potential Indicator: Kg C6H6-e



water pump

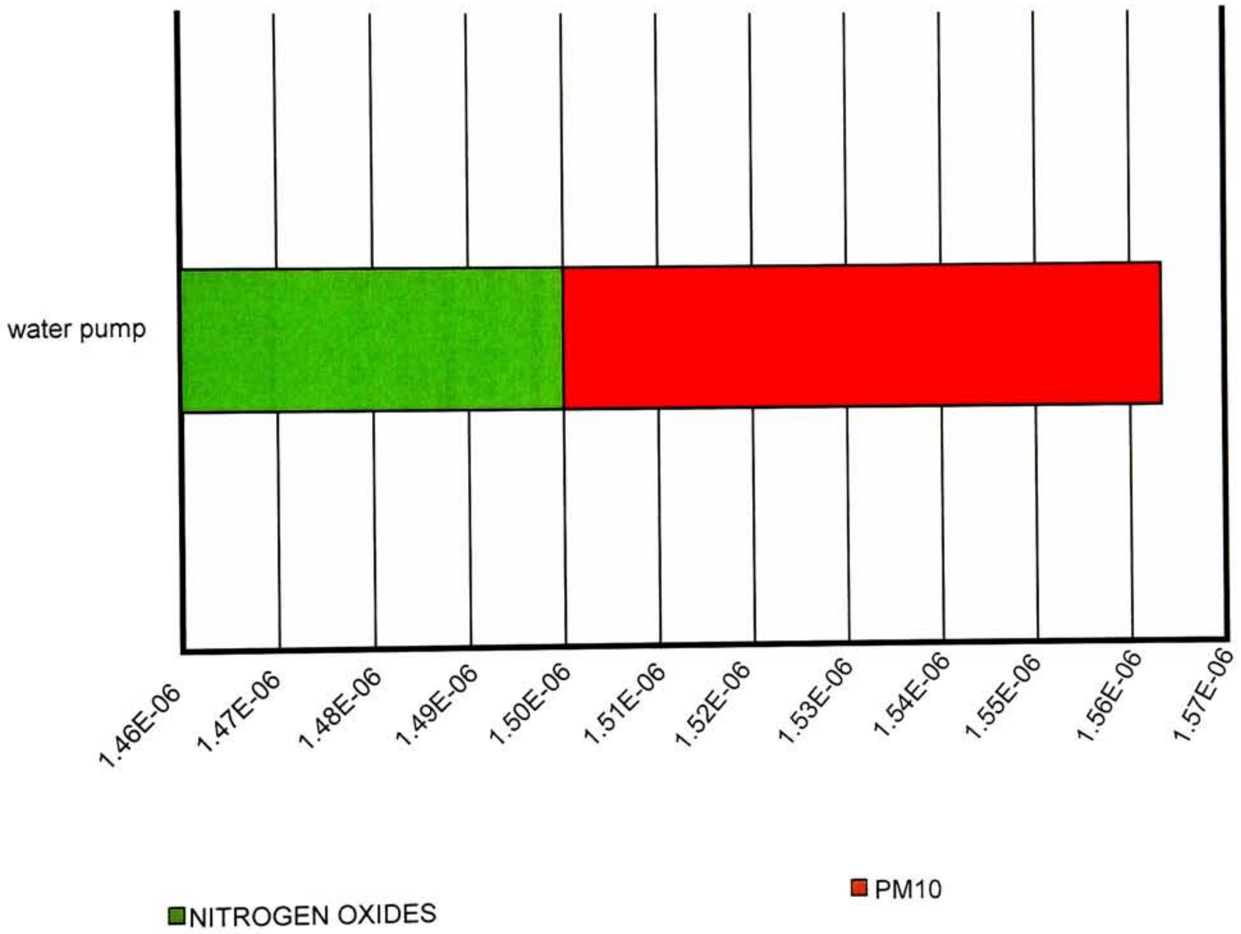
Resource/Release	Characterization Result
ARSENIC	4.57E-06
BENZO(A)PYRENE	8.92E+00
CHROMIUN	0.00E-00
DICHLORO 2.2 DICHLOROETHANE	7.93E-06
IODOMETHANE	1.24E-01
LEAD	6.42E-07
NA	2.63E-03
NICKEL	3.16E-07
SULFURIC ACID, DIETHYLESTER	1.13E-06
VCM	2.56E-06

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for manufacturing

Impact Type: Human Health Criteria

Equivalency Potential Indicator: DALYs



Water pump

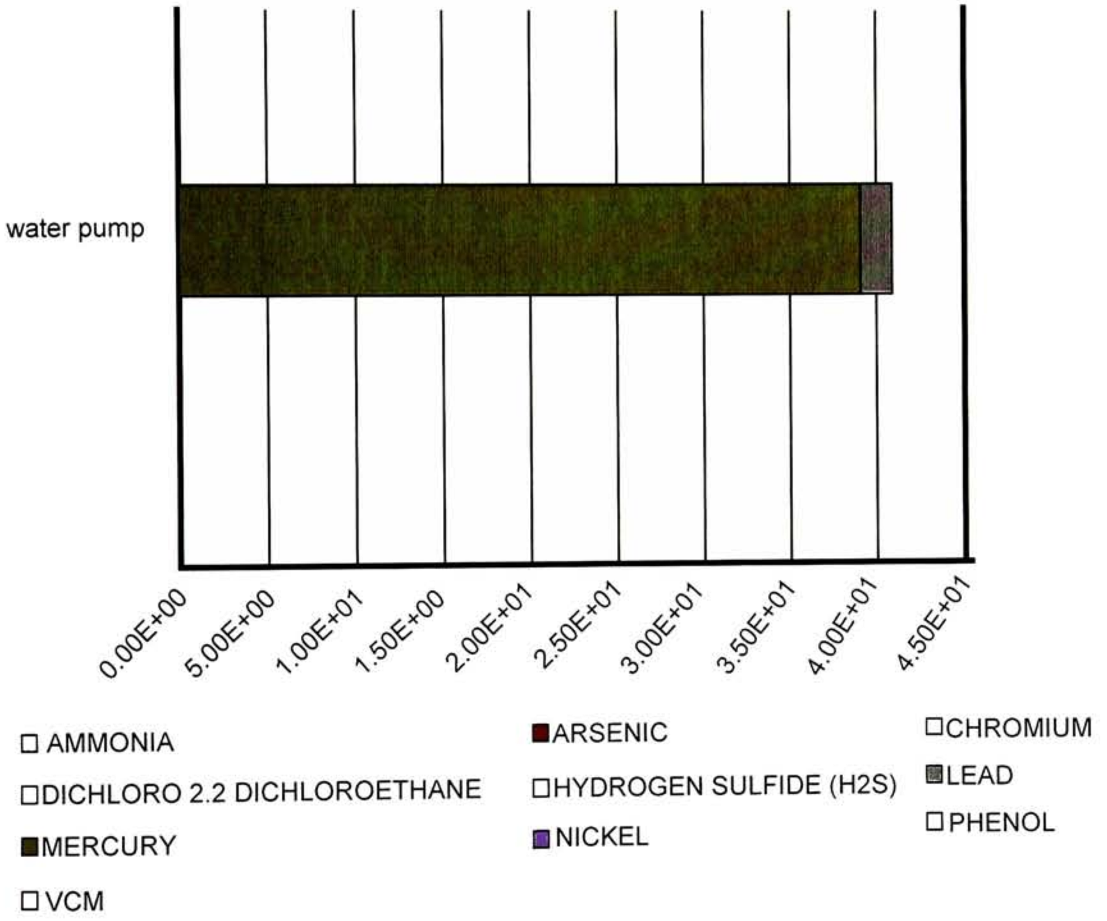
Resource/Release	Characterization Result
NITROGEN OXIDES	1.50E-06
PM10	6.34E-08

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for manufacturing

Impact Type: Human Health Noncancer

Equivalency Potential Indicator: Kg C7H8-e



water pump

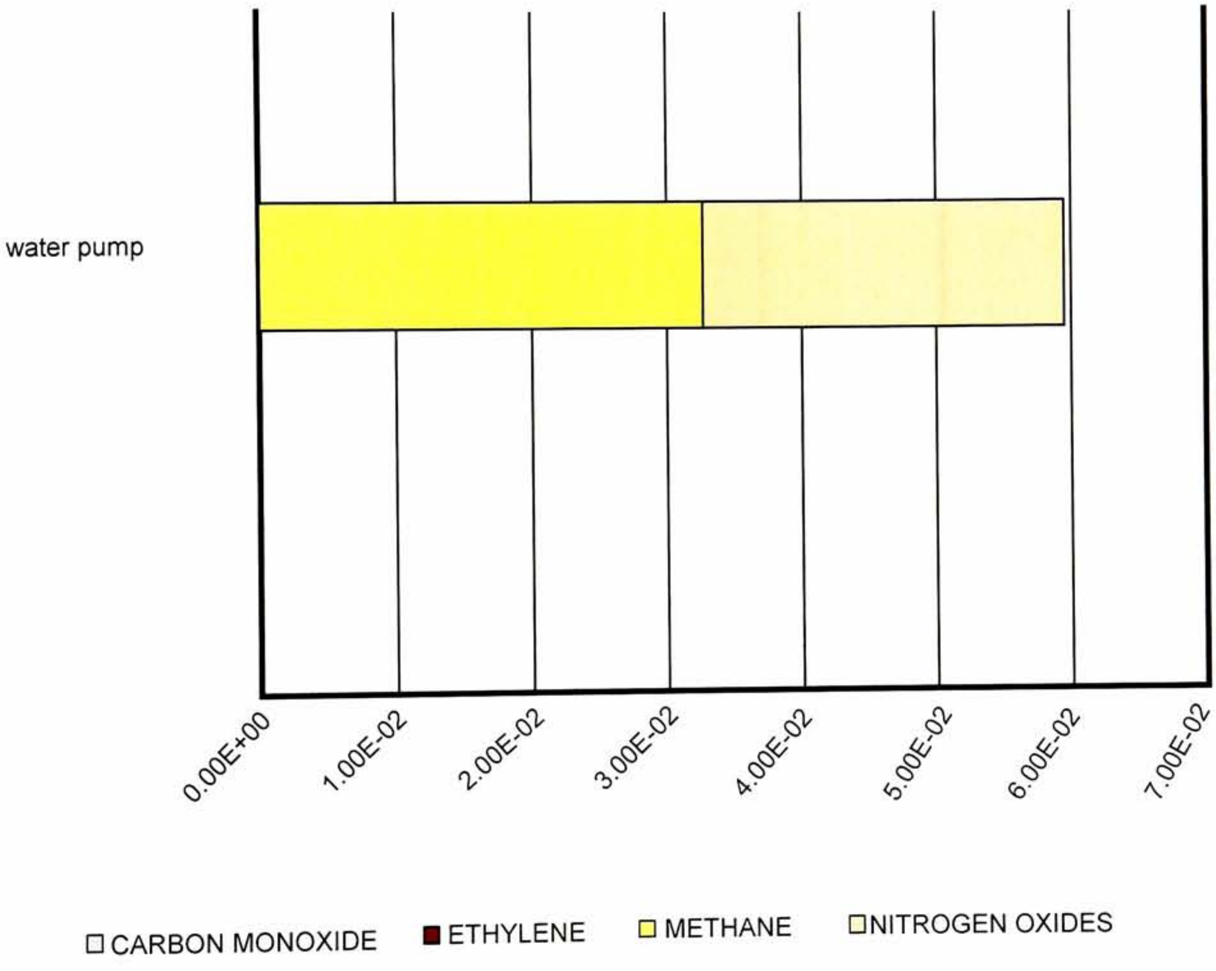
Resource/Release	Characterization Result
AMMONIA	8.52E-06
ARSENIC	2.88E-04
CHROMIUN	1.29E-02
DICHLORO 2.2 DICHLOROETHANE	3.80E-06
HYDROGEN SULFIDE (H2S)	1.07E-09
LEAD	2.73E-02
MERCURY	4.10E+01
NICKEL	7.24E-04
PHENOL	2.67E-08
VCM	4.45E-04

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for manufacturing

Impact Type: Photochemical Smog

Equivalency Potential Indicator: g NOx-e



water pump

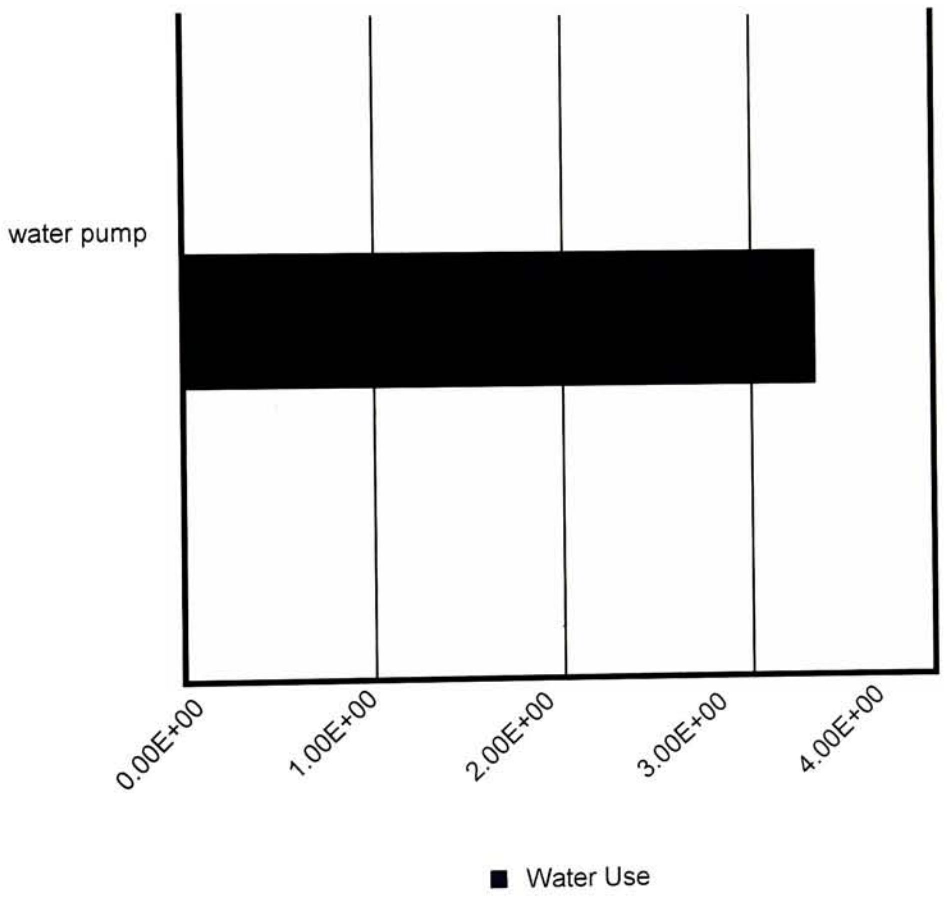
Resource/Release	Characterization Result
CARBON MONOXIDE	4.14E-04
ETHYLENE	1.87E-07
METHANE	3.50E-02
NITROGEN OXIDES	3.13E-02

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for manufacturing

Impact Type: Water Use

Equivalency Potential Indicator: L



Water pump

Resource/Release	Characterization Result
Water Use	3.23E+00

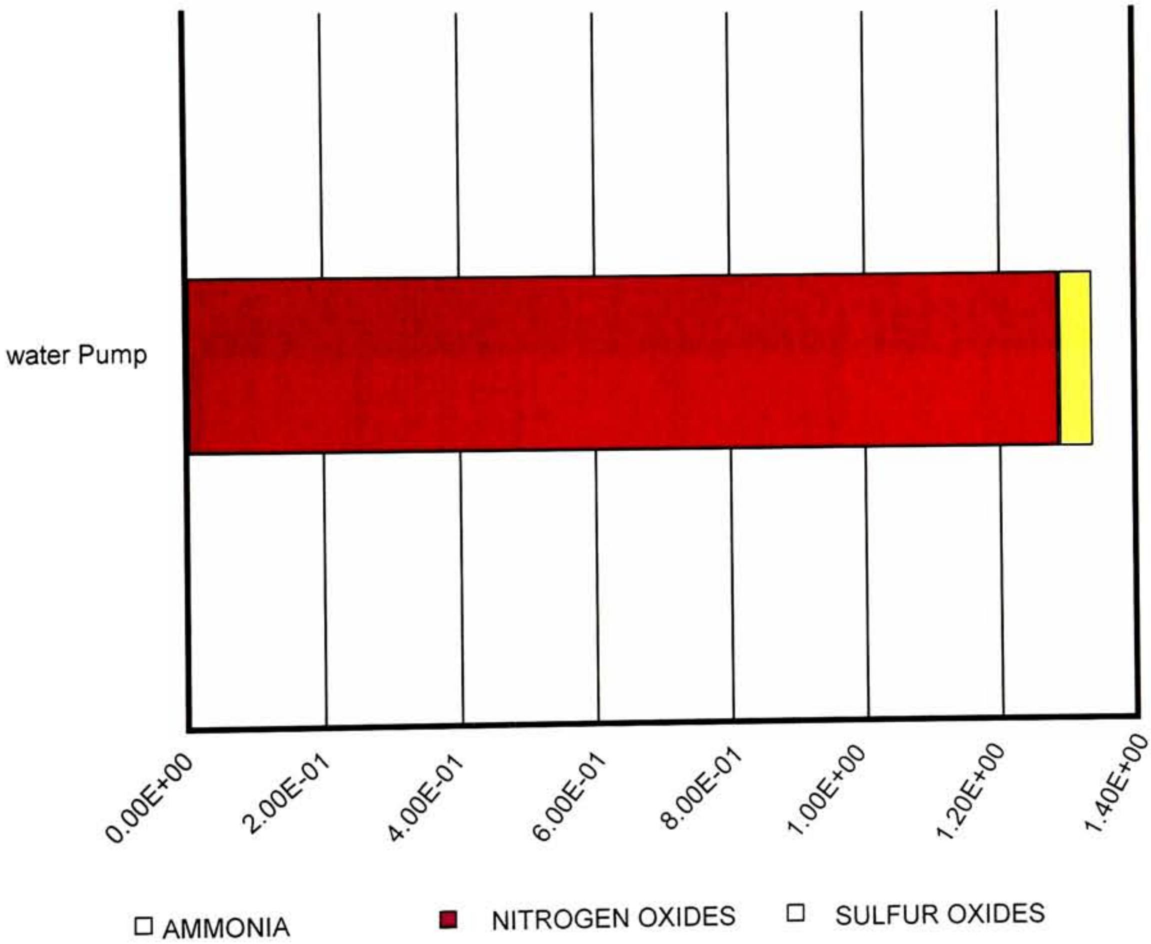
TRACI -Remanufacturing Results

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for remanufacturing

Impact Type: Acidification

Equivalency Potential Indicator: moles H + -e



water pump

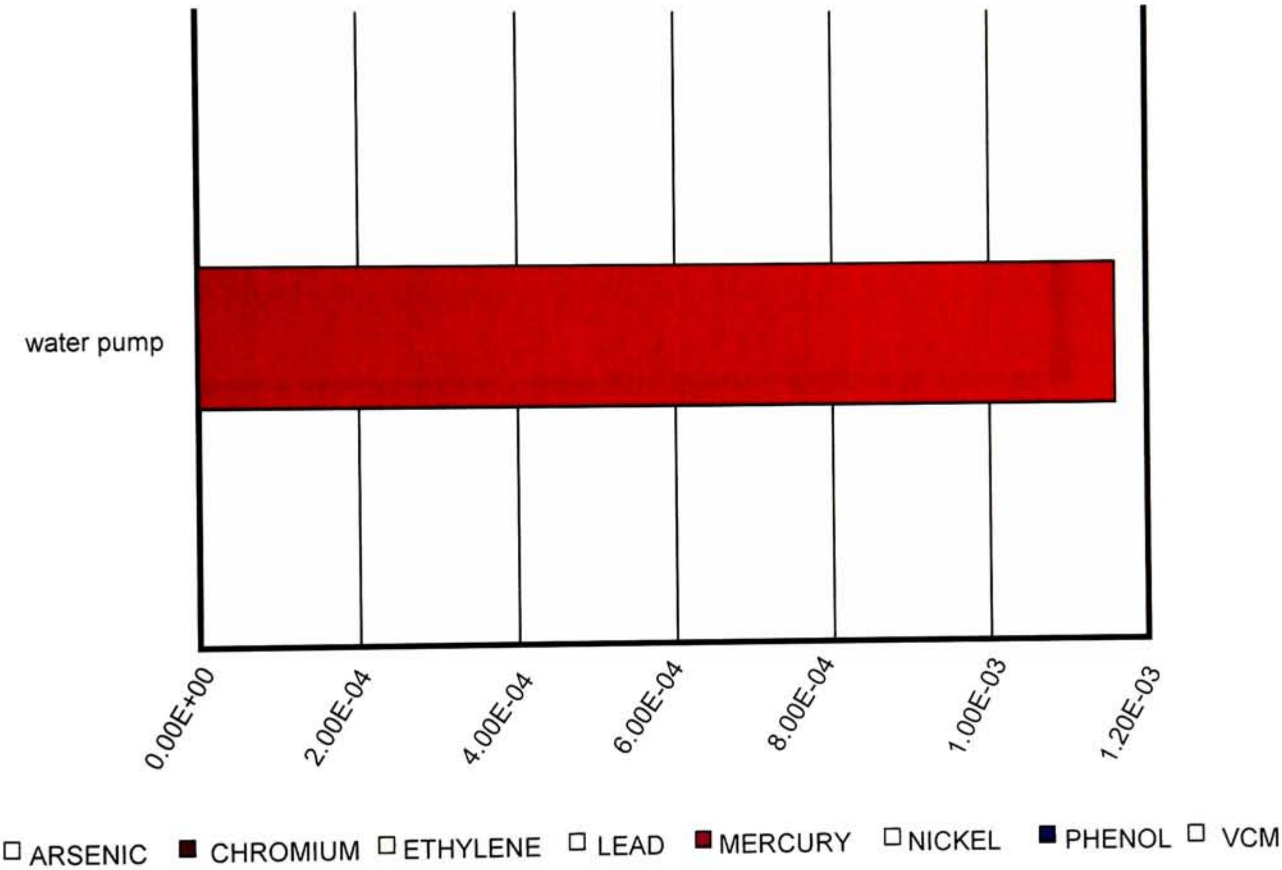
Resource/Release	Characterization Result
AMMONIA	3.74E-05
NITROGEN OXIDES	1.31E+00
SULFUR OXIDES (SOX)	3.38E-02

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for remanufacturing

Impact Type: Ecotoxicity

Equivalency Potential Indicator: Kg 2,4-D-e



Water pump

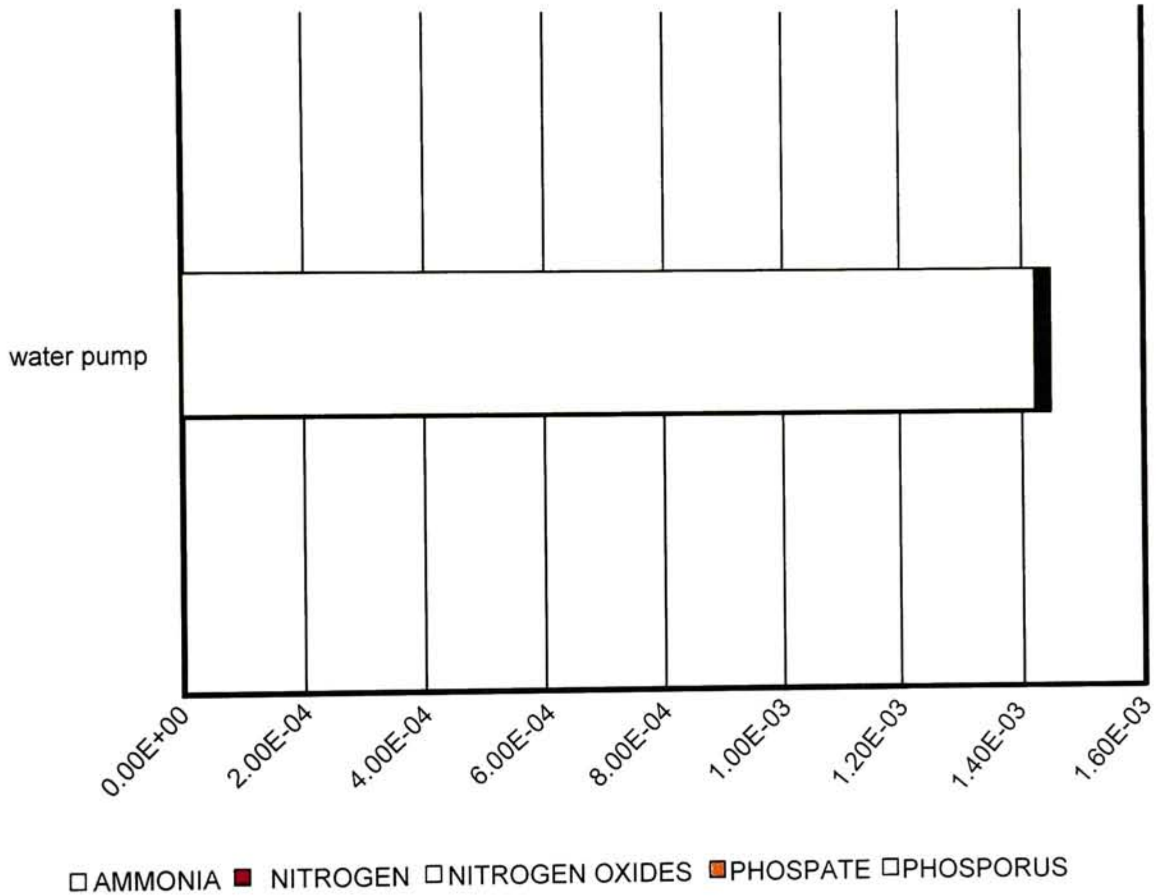
Resource/Release	Characterization Result
ARSENIC	1.29E-08
CHROMIUM	3.09E-10
ETHYLENE	7.28E-12
LEAD	6.75E-08
MERCURY	1.18E-03
NICKEL	4.80E-09
PHENOL	6.39E-08
VCM	3.55E-10

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for remanufacturing

Impact Type: Eutrophication

Equivalency Potential Indicator: Kg N-e



Water pump

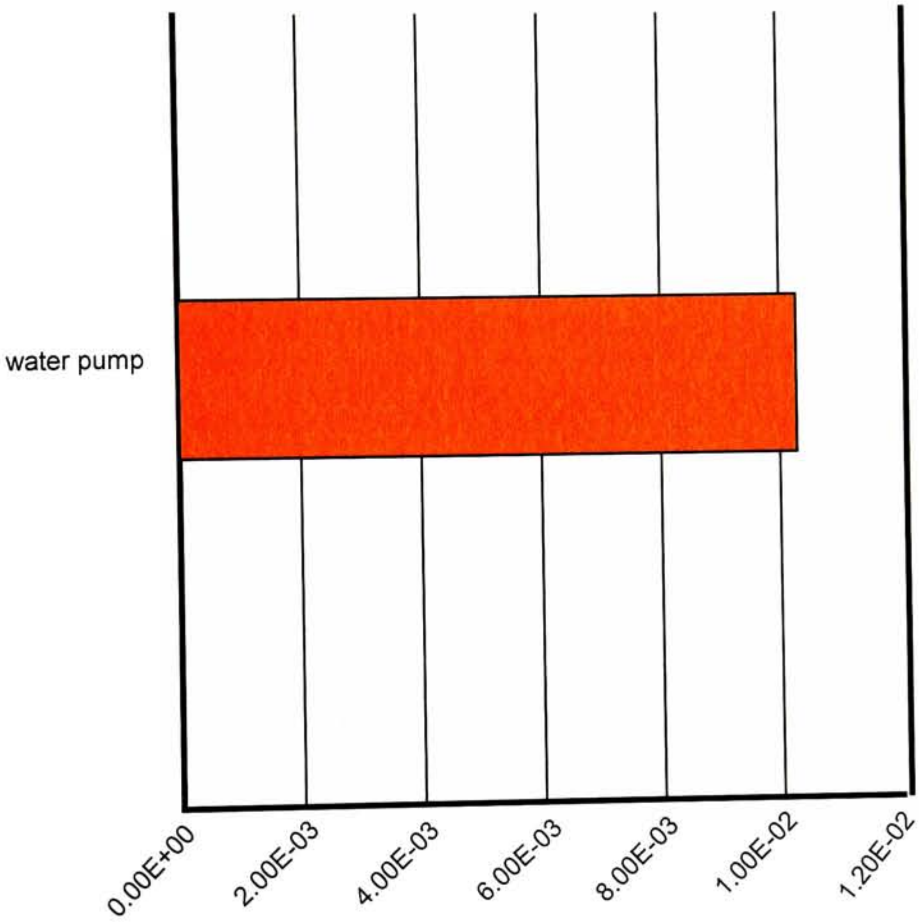
Resource/Release	Characterization Result
AMMONIA	4.65E-08
NITROGEN	2.46E-08
NITROGEN OXIDES	1.45E-03
PHOSPHATE	2.64E-06
PHOSPHORUS	1.04E-05

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for remanufacturing

Impact Type: Fossil Fuel Hard Coal

Equivalency Potential Indicator: MJ surplus



Water pump

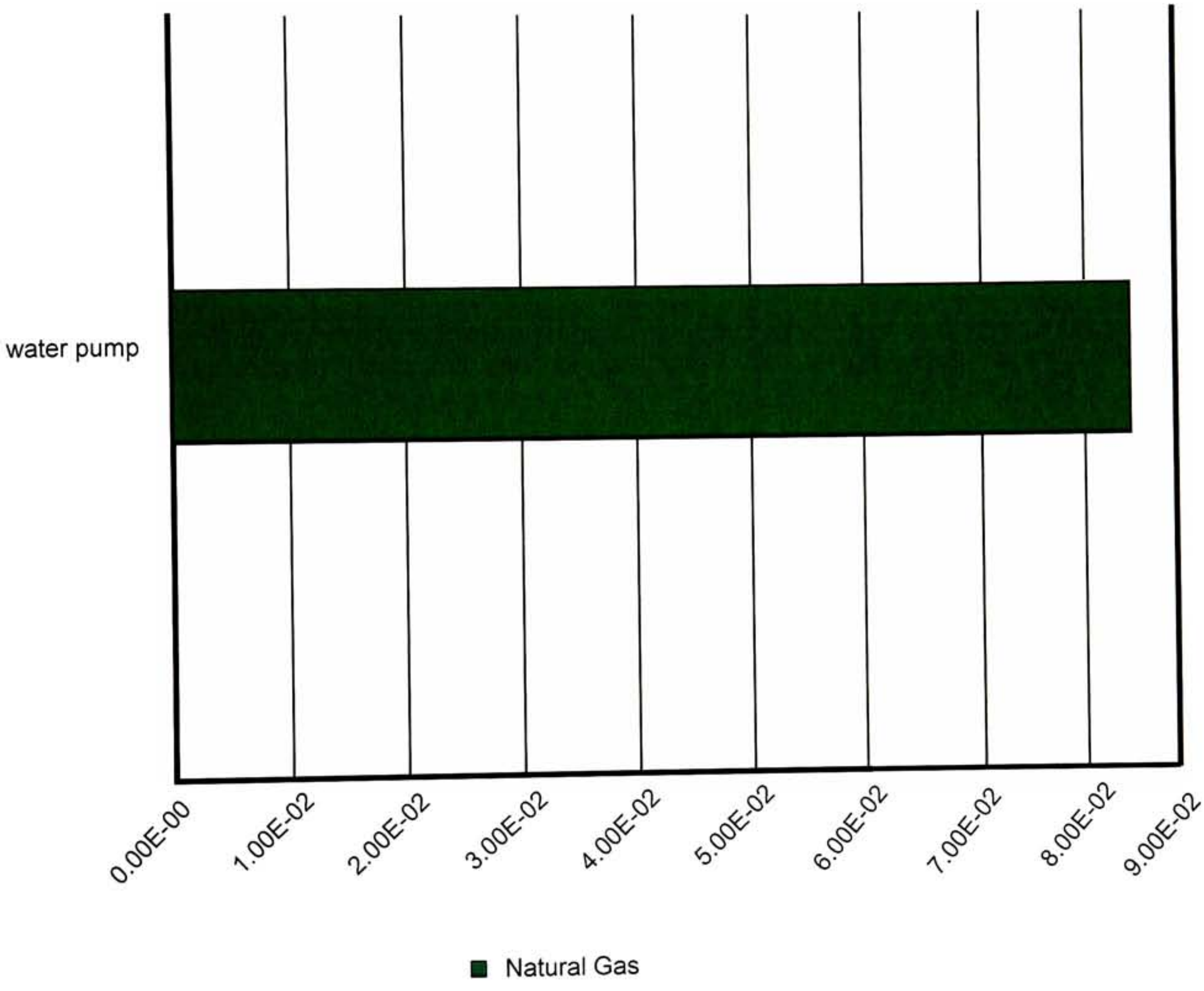
Resource/Release	Characterization Result
COAL	1.01E-02

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for remanufacturing

Impact Type: Fossil Fuel Natural Gas

Equivalency Potential Indicator: MJ surplus



Water pump

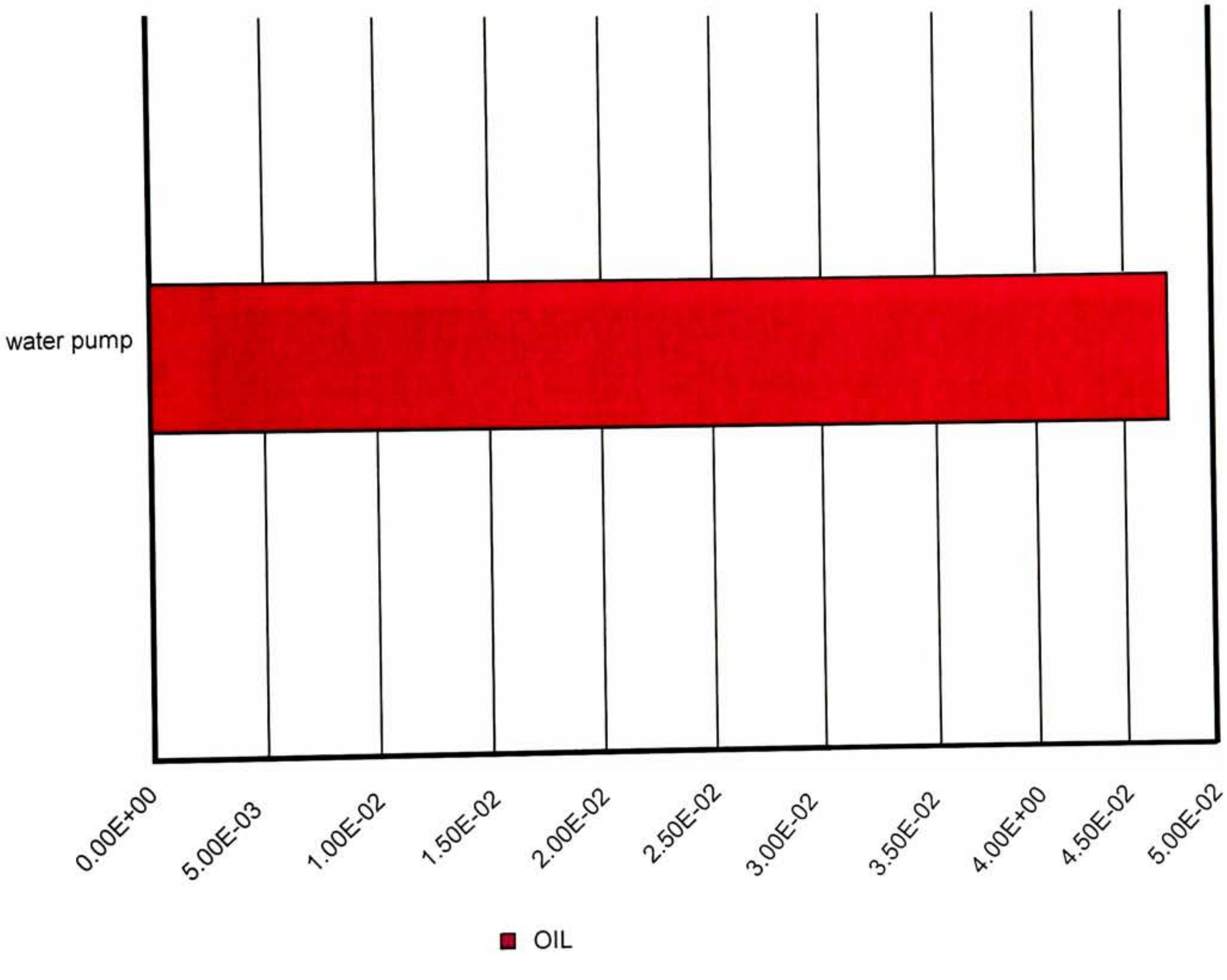
Resource/Release	Characterization Result
NATURAL GAS	8.55E-02

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for remanufacturing

Impact Type: Fossil Fuel Oil

Equivalency Potential Indicator: MJ surplus



Water pump

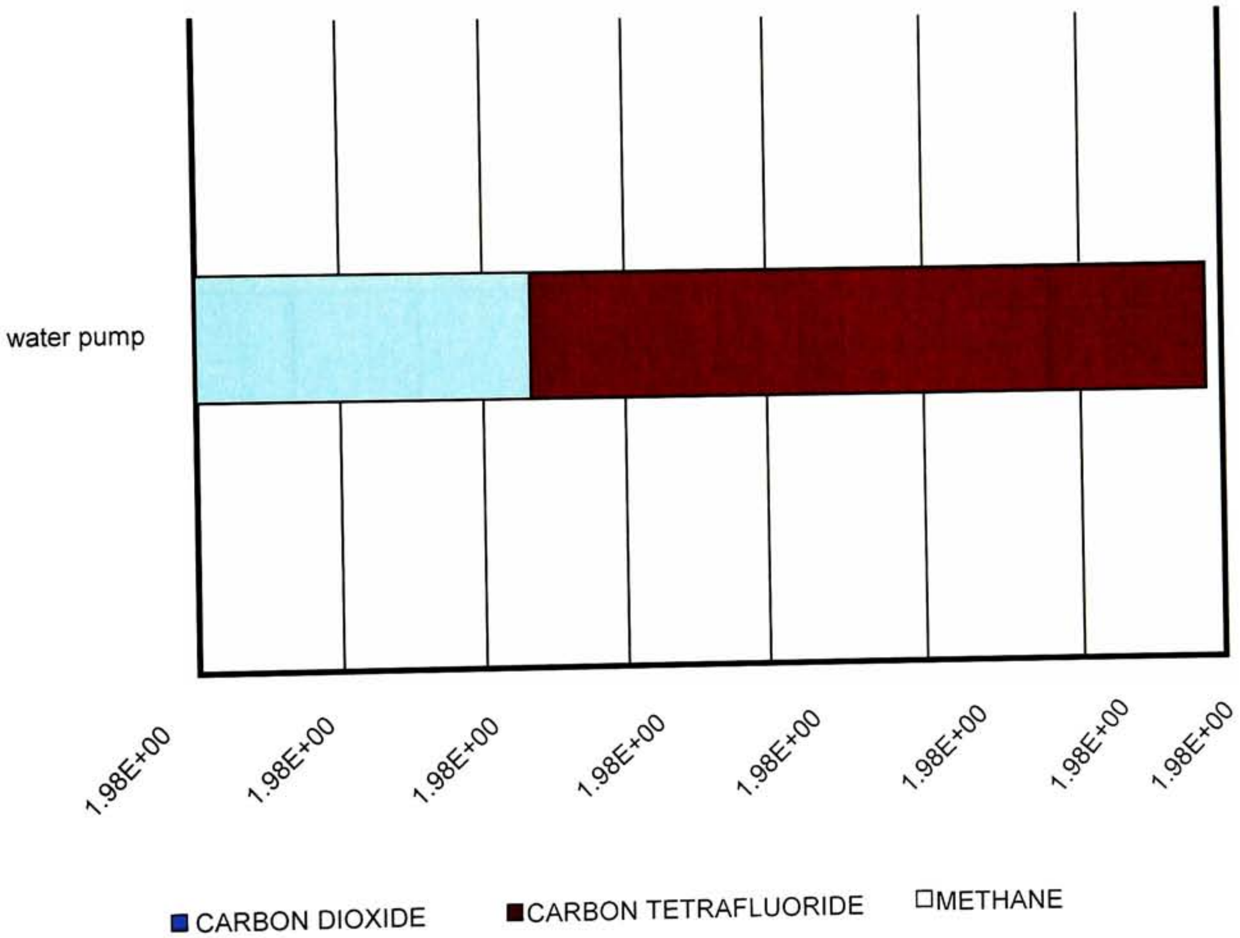
Resource/Release	Characterization Result
OIL	4.76E-02

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for remanufacturing

Impact Type: Global Warming

Equivalency Potential Indicator: Kg CO2-e



Water pump

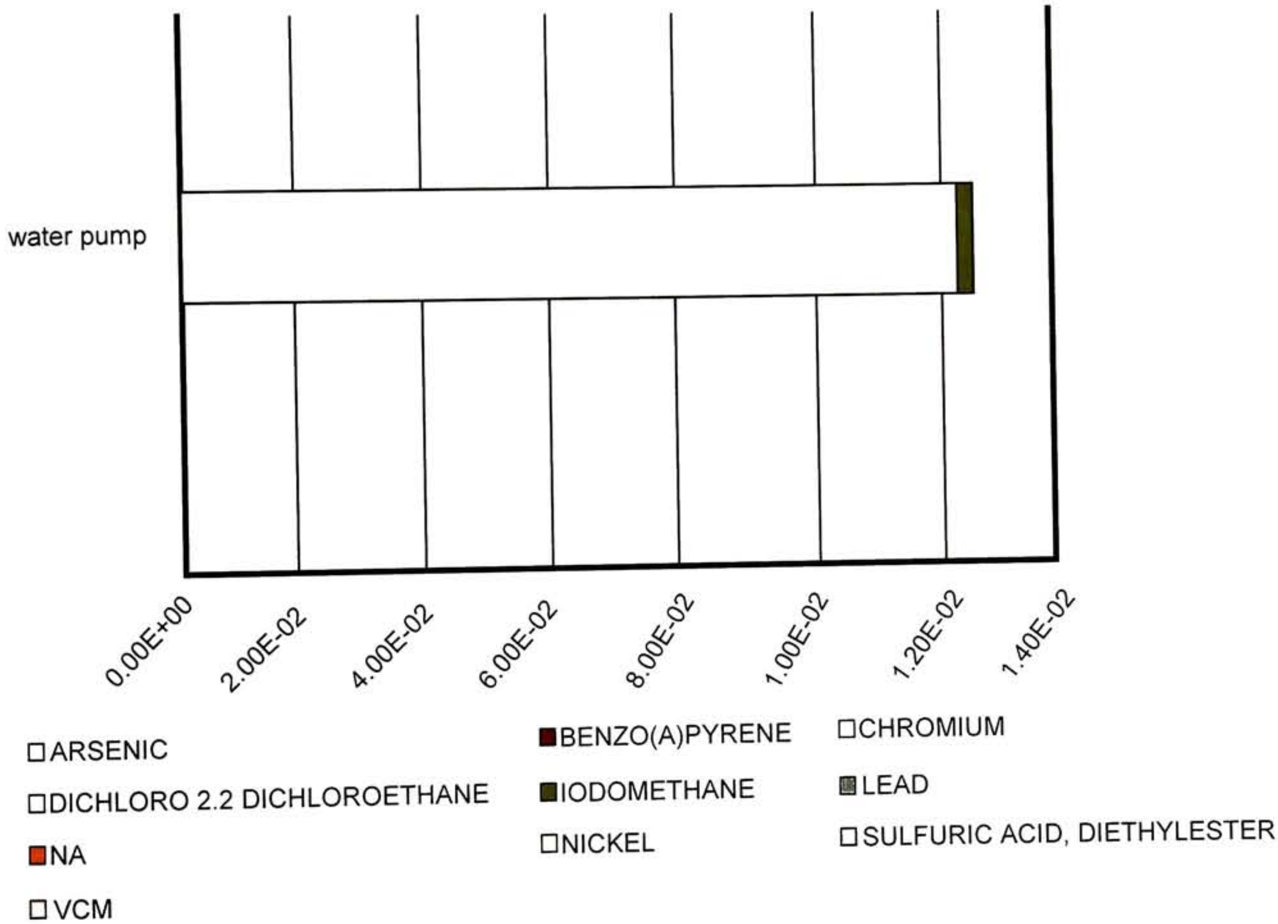
Resource/Release	Characterization Result
CARBON DIOXIDE	1.98E-00
METHANE	2.27E-03

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for remanufacturing

Impact Type: Human Health Cancer

Equivalency Potential Indicator: Kg C6H6-e



water pump

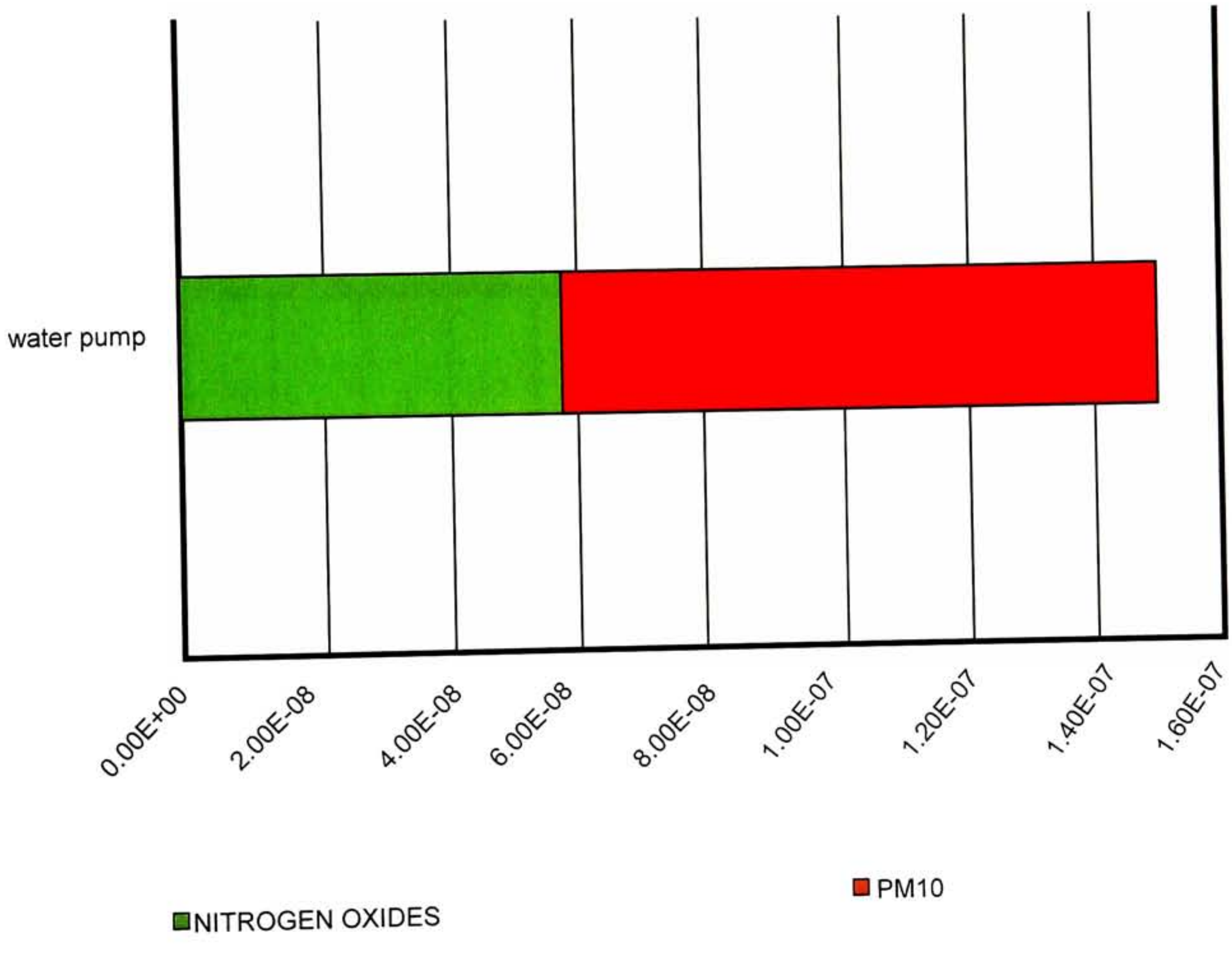
Resource/Release	Characterization Result
ARSENIC	4.57E-06
CHROMIUN	0.00E-00
DICHLORO 2.2 DICHLOROETHANE	7.93E-06
IODOMETHANE	1.24E-01
LEAD	1.04E-07
NA	2.63E-03
NICKEL	0.00E+00
SULFURIC ACID, DIETHYLESTER	1.13E-06
VCM	2.56E-06

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for remanufacturing

Impact Type: Human Health Criteria

Equivalency Potential Indicator: DALYs



Water pump

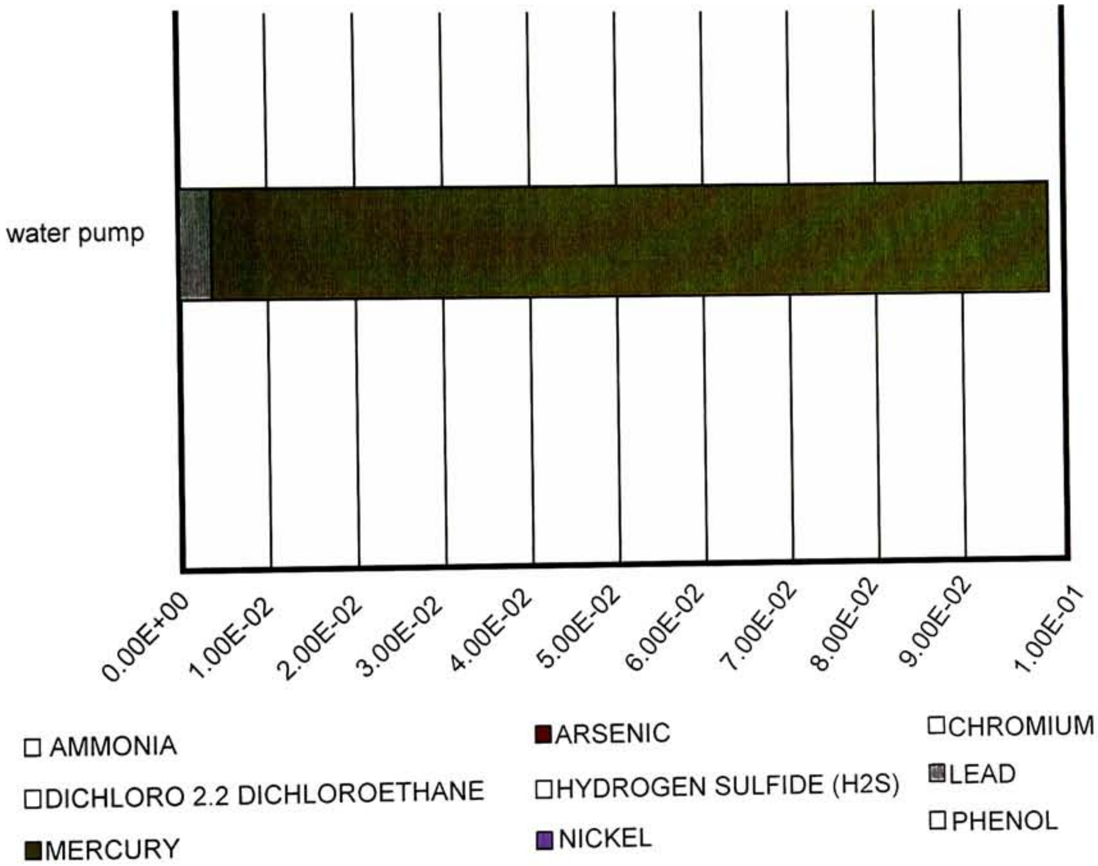
Resource/Release	Characterization Result
NITROGEN OXIDES	7.26E-08
PM10	7.93E-08

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for remanufacturing

Impact Type: Human Health Noncancer

Equivalency Potential Indicator: Kg C7H8-e



water pump

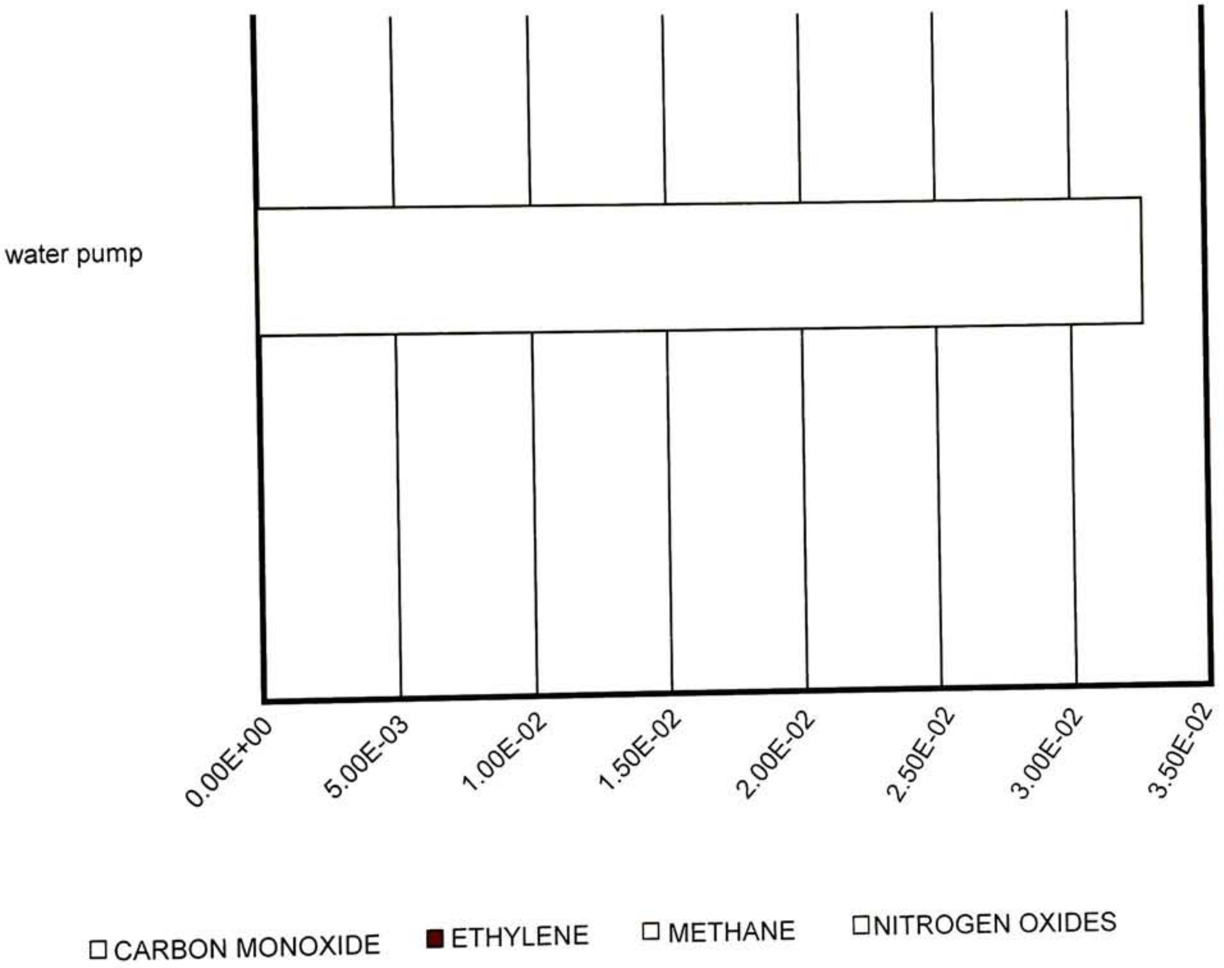
Resource/Release	Characterization Result
AMMONIA	1.25E-06
ARSENIC	2.88E-04
CHROMIUN	4.09E-07
DICHLORO 2.2 DICHLOROETHANE	3.80E-06
HYDROGEN SULFIDE (H2S)	1.07E-09
LEAD	4.42E-03
MERCURY	9.44E-02
NICKEL	1.00E-08
PHENOL	3.69E-10
VCM	4.45E-04

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for remanufacturing

Impact Type: Photochemical Smog

Equivalency Potential Indicator: g NOx-e



water pump

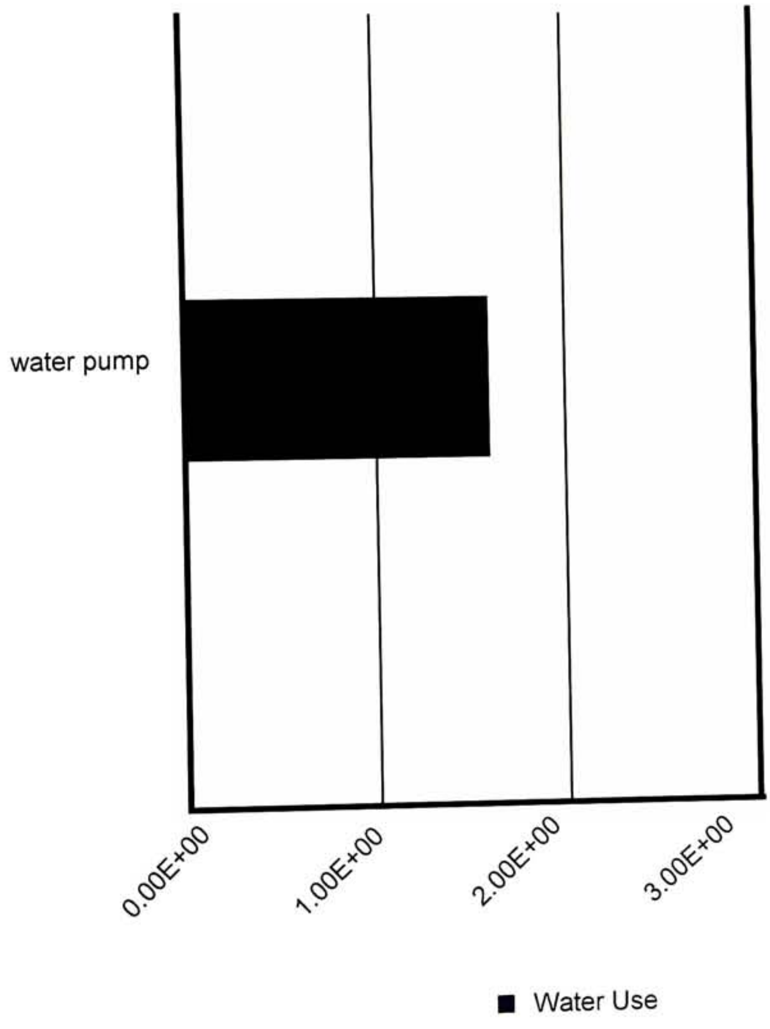
Resource/Release	Characterization Result
CARBON MONOXIDE	1.01E-04
ETHYLENE	1.87E-07
METHANE	3.20E-07
NITROGEN OXIDES	3.28E-02

Resources/Releases at the Product Level

Project Title: Entire water pump analysis for remanufacturing

Impact Type: Water Use

Equivalency Potential Indicator: L



Water pump

Resource/Release	Characterization Result
Water Use	1.50E+00

Appendix B- Energy Conversion

Since the only way to input energy resources in TRACI, is in form of fossil fuels, it is required to convert the Renewable Energy (ER) to Fossil Fuel energy based (EF). It seems that TRACI only take into account the fossil fuel energy because these source of energy account for resource depletion since they are non-renewable sources.

According to general standards Fossil Fuels account from 60 – 80% in the generation of electricity in the United States, meaning coal, oil and natural gas represents the major source of energy production. (*Source*: www.eia.doe.gov)
National standards currently used to generate electricity from fossil fuels.

Coal= 53%
Oil= 3% — 74% of electricity comes from fossil fuels sources.
Ng=18%

It is important to understand that in the process of converting fossil fuel to electricity energy loss occur when transforming the energy from one way to another.

- **Energy Conversion**

The energy content of fossil fuels is:

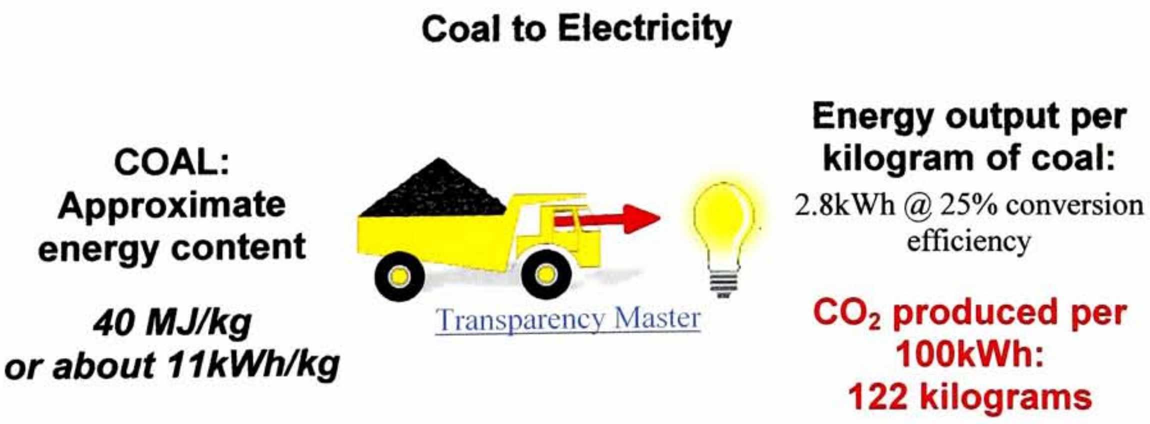


Figure 8.1 Coal to electricity conversion.

Figure 8.2 Oil to electricity conversion.

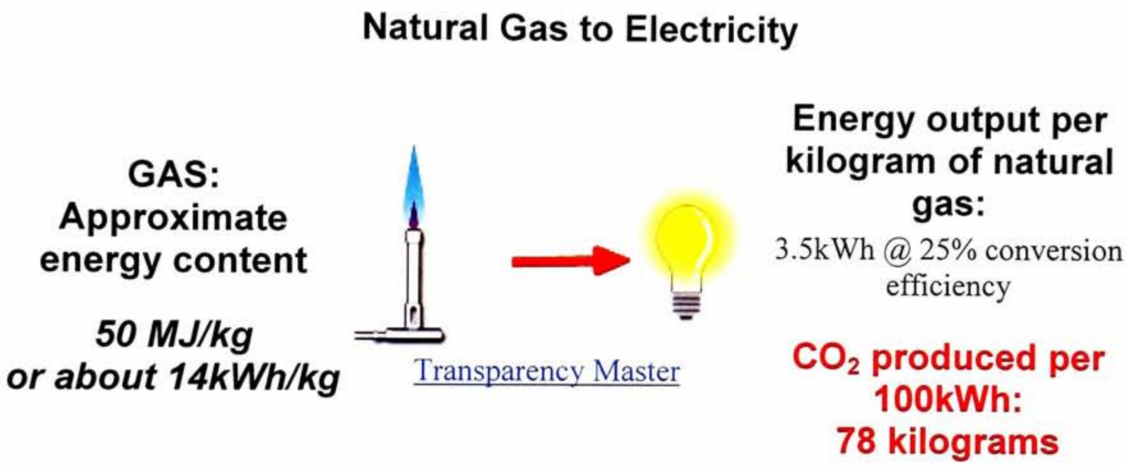


Figure 8.3 Natural Gas to electricity conversion.

After understanding the national standards and the energy content of fossil fuel, we can start the energy conversions.

- FOR ALUMINUM MATERIAL

Converting renewable energy E_R to fossil fuel energy based E_F

Renewable Energy required for producing 1 kg of Aluminum = 57.56 MJ

Fossil Fuel	**To produce 1 kg of aluminum (MJ)**	**Standards**	**MJ**
Coal	57.65	0.53	30.52 MJ
Oil	57.65	0.03	1.73 MJ
Natural Gas	57.65	0.18	10.37 MJ

For coal:

1 short ton of coal =20,681,000 BTU which is the same that
907 kg of coal= 21820 MJ meaning that 1 kg of coal is about 24.06 MJ

If ,

1 kg of coal =24.06 MJ then ⟶ 30.5 MJ = 1.26 kg of Coal

In order to use the **coal to electricity** correlation presented in figure 8.1 we need to express the energy in terms of kg of coal to find out the energy output per kilogram of the fuel.

Therefore,

1kg of coal = 2.8kwh=10.8 MJ then⟶ 1.26 kg of coal is equivalent to <u>13.41 MJ</u>

For oil:

If,

3.26 kg of oil=146.7 MJ then ⟶ 1.73 MJ = 0.038 kg of oil

In order to use the **oil to electricity** correlation presented in figure 8.2 we need to express the energy in terms of kg of oil to find out the energy output per kilogram of the fuel.

Therefore,

1 kg of oil = 2.8 kwh=10.8 MJ then ⟶ 0.038kg of oil is equivalent to <u>0.41 MJ</u>

For Natural Gas:

1 cubic meter of Ng= 38.64 MJ then ⟶ 10.37 MJ =0.268 cubic meter

1 cubic meter = 0.8 kg then ⟶ 0.268 cubic meter = 0.2144 kg

In order to use the **natural gas to electricity** correlation presented in figure 8. 3 we need to express the energy in terms of kg of oil to find out the energy output per kilogram of the fuel.

Therefore,

I kg of Ng= 3.5 kwh =12.6 MJ, then ⟶ 0.2144 kg of Ng is equivalent to <u>2.70 MJ</u>

The same conversion process was performed for Steel and PVC materials, for manufacturing, remanufacturing and recycling data.

- FOR ALUMINUM MATERIAL

Fossil fuel	Energy (MJ)
Coal	13.41
Oil	0.41
Natural Gas	2.70

Table 8.1 ER in terms of fossil fuel to produce 1 kg of Aluminum

Energy conversion for Remanufacturing 1 kg of Aluminum

ER involved in the remanufacturing process of 1 kg of aluminum= 0.55 kwh

Fossil fuel	Energy (MJ)
Coal	0.47
Oil	0.014
Natural Gas	0.11

Table 8.2 ER in terms of fossil fuel to remanufacture 1 kg of aluminum

EF involved in the recycling process of 1 kg of aluminum

Fossil fuel	Energy (MJ)
Coal	0.461
Oil	0.317
Natural Gas	5.395

Table 8.3 EF for recycling 1 kg of aluminum

- FOR STEEL MATERIAL

Renewable Energy required for producing 1 kg of Steel = 0.352 MJ

Fossil fuel	Energy (MJ)
Coal	0.083
Oil	0.0025
Natural Gas	0.0016

Table 8.4 ER in terms of fossil fuel to produce 1 kg of steel

Renewable Energy required to remanufacture 1 kg of Steel = 0.6 kwh= 2.16 MJ

Fossil fuel	Energy (MJ)
Coal	0.5026
Oil	0.0155
Natural Gas	0.1014

Table 8.5 ER in terms of fossil fuel to remanufacture 1 kg of steel

Renewable Energy required to recycle 1 kg of Steel = 0.93 MJ

Fossil fuel	Energy (MJ)
Coal	0.2163
Oil	0.0066
Natural Gas	0.044

Table 8.6 ER in terms of fossil fuel to recycle 1 kg of steel

- FOR PVC MATERIAL

Renewable Energy to produce 1 kg of PVC

	Renewable Energy (MJ)
EDC	14.59 MJ
VCM	14.57 MJ
PVC	12.61 MJ
Total	**41.95 MJ**

Fossil fuel	Energy (MJ)
Coal	9.978
Oil	0.302
Natural Gas	1.969

Table 8.6 ER in terms of fossil fuel to produce 1 kg of PVC

Renewable Energy for the Injection Molding Process for 1 kg of PVC = 1.05 kwh = 3.78MJ

Fossil fuel	Energy (MJ)
Coal	0.899
Oil	0.027
Natural Gas	0.177

Appendix C- Cleaning Technologies for Remanufacturing

- Cleaning technology recommended for Aluminum remanufacturing
  - *High or Medium Pressure Spray*

Part to be remanufactured: Aluminum Housing

Equipment: Mart Cyclone 30 Spray Cabinet

Chemistry: Brulin and Armakleen – No air emissions related to those chemicals

Cost per 100 parts = 5.49 /100 =0.0549

Cost per unit (Aluminum Housing) = $ 0.055

Energy Cost = 0.10/ kwh (assuming ER) Hydro

The cost for remanufacturing the aluminum housing of the WP is approximately $0.055 and the energy for the remanufacturing process is 0.55 kwh/unit

- Cleaning technology recommended for Steel remanufacturing
  - *Vibratory Degreaser*

Equipment – Vicking Model 4S shaker

Part name	$Cost/unit
Shaft Bearing	0.030/unit
Impeller	0.010/unit
Mounting plate	0.015/unit
Hub (shaft)	0.005/unit
Metal Spring	0.001/unit
Metal Ring	0.001/unit

The table above shows the cleaning costs for remanufacturable water pump parts.

The cleaning technologies and cleaning costs were suggested by a confidential industry in the water pump remanufacturing business. Also, personal from the National Center For Remanufacturing and Resource Recovery contributed with suggestions about cleaning technologies.

Appendix D- Emissions resulting from Transportation

Emission Factors	**Greater Than or Equal to 600HP (lb/hp-hr)**	**Kg of emission/hr**
Particulate Material- PM10	0.0007	0.19
Sulfur Dioxide-SO2	0.0004045	0.11
Nitrogen Oxides-NOx	0.024	6.53
Volitile Organic Compounds-VOC	0.000705	0.19
Carbon Monoxide -CO	0.0055	1.496

Source: EPA AP 42, 3.3 Gasoline and Diesel Industrial Engines & 3.4 Large Stationary Diesel and all Stationary Dual-Fuel Engines 10/96

These were the chemical emissions utilized through the length of this research for transportation of materials.

It is assumed that the entire water pump is being transported at once. For that reason, outputs shown in LCI graphics 4.6, 4.9 and 4.11 correspond to transportation emissions divided by 3 (per each one of the three 3 material) .

Appendix E- Emission factors to calculated CO_2 emissions resulting from electricity

Fuel Type	**Emission factor (kg CO_2/kwh)**
Coal	0.960
Oil	0.870
Natural Gas	0.597

Source: Carbon Dioxide Emissions from the Generation of Electric Power in the United States, July 2000 (Department of Energy/EPA).

These emission factors were used to estimate CO_2 emission resulting from energy consumption for aluminum, steel and PVC.

Appendix F- [1]Materials LCI

- Aluminum Material

1) Life Cycle Assessment Of Aluminum: Inventory Data For The Worldwide Primary Aluminum Industry- March 2003. (Year 2000 Aluminum LCI Report for the International Aluminum Institute).
2) Aluminum Applications and Society: Life Cycle Inventory of the Worldwide Aluminum Industry With Regard to Energy Consumption and Emissions of Greenhouse Gases. Paper 1- May 2000 (LCI Report for International Primary Aluminum Institute).
3) Remanufacturing Data For Aluminum Housing WP component- (confidential source).

- For Steel Material

1) LCI Results for 1 kg of Steel /Primary Production. "Industry Sector Report for The United Nations World Summit on Sustainable Development" International Iron and Steel Institute, January 2002.
2) LCI Results for 1 kg of Steel /Secondary Production. "Industry Sector Report for The United Nations World Summit on Sustainable Development" International Iron and Steel Institute, January 2002.
3) Remanufacturing Data For Steel Remanufacturable Parts- (confidential source).

- For PVC Material

1) Ecoprofile Data (European Council of Vinyl Manufacturers-May 1993)
2) Ecoprofiles of Plastics and Related Intermediates (Brussels, 1999)
3) Injection Molding Energy Consumption for 1 kg of PVC (Energy and Environment management in the Plastic Forming Industry of Ho Chi Minh City-August 2002.

[1] Refer to references.

APENDIX G- TRACI Units

IMPACT CATEGORY	UNITS
Acidification	H+ moles equivalents /kg emission
Ecotoxicity	2,4,D equivalents/kg emission
Eutrophication	Nitrogen equivalents/kg
Global Warming	CO2 equivalents/kg emission
Human Health Cancer	Benzene equivalents/kg emission
Human Health Non-Cancer	Toluene equivalents/kg emission
Human Health Criteria	DALYs
Ozone Depletion	CFC-11 equivalents/kg emission
Photochemical Smog	g NOx equivalents/Kg emission
Fossil Fuel Depletion	MJ surplus energy/MJ of extracted energy
Water Use	L