Design of a Remanufacturing Process for an Air Conditioning Unit and its Environmental Implications.

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Design of Remanufacturing Process of an Air Conditioner Unit and its Environmental Implications

By

Aiman Ziout

A Thesis
Submitted to the Faculty of Graduate Studies through the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Applied Science at the University of Windsor

Windsor, Ontario, Canada

2018

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Design of Remanufacturing Process of an Air Conditioner Unit and its Environmental Implications

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AUTHOR’S DECLARATION OF ORIGINALITY

I hereby certify that I am the sole author of this thesis and that no part of this thesis has been published or submitted for publication.

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I declare that this is a true copy of my thesis, including any final revisions, as approved by my thesis committee and the Graduate Studies office, and that this thesis has not been submitted for a higher degree to any other University or Institution.
Remanufacturing is considered as the most preferable recovery option. The objective of this thesis is to verify this claim and test its validity. A window-mount air conditioner (AC) is selected as a case study to verify the environmental benefits of remanufacturing a product characterized by high energy consumption during the use phase in its lifecycle. A lifecycle approach has been followed. The research investigates the environmental savings in regard to a remanufactured AC compared to a new and equivalent AC. The assessment is conducted with the guidance of the ISO 14044 -2006 life cycle assessment (LCA). Analysis shows that AC remanufacturing is not always an environmentally attractive option; sensitivity analysis shows that ten percent improvement in energy efficiency of new AC is breakeven point. A new and more efficient AC scored better on three areas related to environmental impacts out of five studied. The significance of this study lies in the fact that it provides an authentic example wherein remanufacturing is not always the environmentally preferred recovery option. The developed lifecycle model can be utilized to help AC manufacturers make decisions about the overall environmental performance of their products.
DEDICATION

I dedicate this work to whom its accomplishment was at the expense of their time.

I dedicate this work to my wife Haya and my four little angels: Sora, Basheer, Fatemah, and Adam.
I’d like to recognize and thank my supervisors, Dr. Ahmed Azab and Dr. N. Biswas, for the support they have provided me during the years of my research. Thanks for all what they have done to make this work valuable.

I’m also thankful for my thesis examination committee members: Dr. Fazle Baki and Dr. Rajesh Seth. Their invaluable feedback and comments greatly shaped this work, and contributed to its high quality.

Great thanks are due to the industrial partner, for opening their heart as well as their plant for this research. They were supportive and interested in the findings of this research. They provided me with access to quality case studies, which significantly improved the practical value of this research. Thanks also to the panel of experts who were involved in this project.

Finally, I’d like to acknowledge my family, especially those who live thousands of miles away from me. Despite the distance I always feel very close to their hearts. They always provide me with love and encouragement. I doubt that my little kids, Sora, Basher and Fatimah, understood why I had to leave them during weekends and to go to school early and return home late. I acknowledge their patience. Finally, my deep appreciation goes to my wife, who provided unlimited support during this long and difficult journey.
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LIST OF ACRONYMS

AC  air conditioner
ADP  abiotic depletion potential
AP  acidification potential
BP  British Petroleum
BTU  British Thermal Unit
CFC  chlorofluorocarbon
EEC  European Economic Community
ELCD  European Life Cycle Database
EOL  end-of-life
EIP  energy-intensive products
EP  eutrophication potential
EU  European Union
FWAETP  fresh water aquatic ecotoxicity potential
GWP  global warming potential
GE  General Electric
HVAC  heating, ventilation and air conditioning
HTP  human toxicity potential
HCFC  hydrochlorofluorocarbon
IDEF0  Integrated Computer Aided Manufacturing DEFinition for Function Modeling
ISO  International Organization for Standardization
KSA  Kingdom of Saudi Arabia
KSU  King Saud University
LCA  life cycle assessment
LCI  life cycle inventory
LCIA  life cycle impact assessment
LNG  liquid natural gas
LPG  liquefied petroleum gas
MAETP  marine aquatic ecotoxicity potential
MJ  mega joule
MWh  mega watt hour
OD  ozone depletion
OEM  original equipment manufacturers
ODP  ozone depletion potential
PED  primary energy demand
POCP  photochemical ozone creation potential
R&D  research and development
RAD  radioactive radiation
RoHS  Restriction of Hazardous Substances
SASO  Saudi Standards, Metrology and Quality Organization
TETP  terrestrial ecotoxicity potential
TRACI  Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>US</td>
<td>United States</td>
</tr>
<tr>
<td>VOC</td>
<td>volatile organic compounds</td>
</tr>
<tr>
<td>WEEE</td>
<td>Waste Electrical and Electronic Equipment</td>
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1 INTRODUCTORY CHAPTER

1.1 Introduction

Products at their end-of-life (EOL) go either to landfill or are recovered fully or partially. Product recovery options vary ranging from full recovery through to reuse options to partial material recovery or energy recovery through product incineration.

Remanufacturing is an emerging recovery option, which redevelops the EOL product to a “like new” state. Recovered value through remanufacturing can be higher than recovered value through other recovery options. In the remanufacturing option, EOL products are collected, disassembled, cleaned, reprocessed whenever needed, then inspected, and reassembled to produce a product that has same performance to its equivalent in a new product.

The main motivation behind remanufacturing as well as other recovery options is to maintain sustainable development by saving resources and reducing industry’s environmental burden. Another motivation is the economic profit. Remanufacturers can make profit through the remanufacturing business.

1.2 Problem background and motivation

Air conditioner (AC) remanufacturing, like any other remanufacturing business, is motivated by saving resources, reducing environmental impacts, and generating financial profit. This study investigates the resource saving and environmental impact reduction that can be achieved through remanufacturing AC.

Resources consumption and environmental impacts occur during all phases of a product’s life cycle. This study follows a life cycle approach to perform an investigation
that analyzes resources saving and environmental impacts throughout all the phases in a product’s life cycle. Saving in resources and reduction in environmental impacts require a reference to compare these savings and reductions with, and in this study an equivalent new AC is considered as the reference for comparison.

The analysis is conducted on AC that operates in a hot region (Saudi Arabia) that also has a long summer having temperature that could reach 55°C. Operation in such a climate requires long operating hours, which makes the contribution of the use phase in the product life cycle significant. The case also is sensitive to the source of energy that operates the product. The AC is operated by electricity that is generated mainly (in this case study) through the use of natural gas and crude oil. The environmental impact associated with electricity generation can be linked directly to the use phase of the AC.

1.3 Problem and research question

Air conditioners are energy-use intense products. AC manufacturers are encouraged, sometimes obliged, to develop more energy saving products. The energy efficiency for AC has increased about 47% from 1972 to 1991. The 2015 AC energy efficiency products are 11% more efficient than 1991 models (Energy.gov, 2016). Technologies that facilitate these improvements are not predictable. However, there is a continuing trend to increase AC energy efficiency.

Remanufactured AC is challenged by the fact that new ACs are always more energy efficient than remanufactured ones. This condition prompts a question, “Do the savings found through remanufacturing an old product outweigh the energy savings by buying a new product?”

To address this question, the following queries are set as research questions:
“Does remanufactured AC have less environmental impact than its equivalent in new AC, considering the overall life cycle?”

To answer this research question, the following sub-research questions are formulated:

- What are the environmental impacts of remanufactured AC?
- What are the environmental impacts of newly manufactured AC?
- What is the difference between the environmental impacts of remanufactured AC and new equivalent AC over all their life cycle?

1.4 Research objectives

The main objective of this study is to assess the environmental performance of AC remanufacturing. The study aims to identify the environmental gains and losses of a remanufacturing initiative. More specifically, the study aims to quantify the difference in environmental performance between a remanufactured AC and a new AC with respect to the following four major environmental impacts associated with the AC industry:

2. Gain/loss in ozone depletion potential.
4. Gain/loss of energy.

The above strategic objective is achieved through the following objectives:

- Design of remanufacturing process for the studied AC unit; this is essential to be able to assess the environmental impact of remanufactured AC.
- Identification of life cycle phases of both a remanufactured AC and a new AC.
• Identification of the environmental inventory of the significant life cycle phases of both a remanufactured AC and a new AC.

• Interpretation of identified inventory into environmental impacts.

• Identification of the most environmentally significant processes and phases in the life cycle of the AC.

These objectives are achieved by implementing the methodology in the following section that describes the research approach and methodology.

1.5 Research approach

The research follows a query research approach that answers the research questions through implementing a life cycle approach of a selected product as a case study. A life cycle approach was selected to ensure that all inputs and outputs of the entire life cycle of the studied product system are considered. The case study gives this research the advantage of having real data and the opportunity to implement the results of the research on an actual product.

The research implements the ISO 14044, which provides guidelines for life cycle assessment (LCA) and also specifies requirements in the conducted analysis. It includes the following phases (Figure 1.1 demonstrates these phases and their interaction):

• Definition of the goal and scope of the LCA.

• The life cycle inventory analysis (LCI) phase.

• The life cycle impact assessment (LCIA) phase.

• The life cycle interpretation phase.

This methodology was applied to specific AC produced by a local manufacturer located in the region where the study is conducted. Data was collected from measurements
obtained on site at the manufacturing facility as well as from measurements conducted through reverse engineering of the selected model. The experiments were conducted in a lab environment. Other data was obtained from public databases or commercial databases freely available for educational purposes.

Figure 1-1 Life cycle assessment approach based on ISO 14044 : 2006.

1.6 Research outcomes and significance

The main outcome of this research is a detailed analysis of the environmental performance of AC remanufacturing. As well, it provides a comparative assessment between the life cycle impact of a remanufactured AC and a new AC. These outcomes are significant to the research and development community as it gives insight about the actual performance of a remanufacturing option for an energy-intense product, which in some regions contributes up to 70% of residential electrical consumption. This research is also significant because it:

1. Establishes the fundamental operations in AC remanufacturing process.
2. Helps manufacturers make informed decisions about their AC design considerations and planning its EOL recovery.

3. Helps policy makers and legislators decide about regulations appropriate for EOL AC treatment.

1.7 Research scope and limitations

The scope of this research covers the environmental assessment of AC remanufacturing in comparison with new AC. The scope spans the whole life cycle phases of the product; cradle-to-grave life cycle assessment is adopted in this research.

The research is limited to the studied product, which is a room AC. Other types of AC systems do not necessarily follow the same assumptions applicable to window type AC, and consequently, the same results cannot be drawn without extra verification.

The characteristics and assumptions made about the geographical region limit the results. Such as AC operating conditions, number of operating hours, and distances from sources of EoL product and remanufacturing plant.
2 LITERATURE REVIEW

2.1 Introduction

The goal of sustainable development is, “to ensure socially responsible economic development while protecting the resource base and the environment for the benefit of future generations” (UNCED, 1992). Unsustainable patterns of consumption and production have directed the attention of academic, industrial and governmental organizations toward the conservation of natural resources with a special focus on energy. Although sustainable development is the responsibility of all citizens, manufacturers bear the greatest responsibility. The manufacturing sector in the United States, for example, consumes (21%) of the total energy output of that country (U.S. Energy Information Administration, 2015). The role of manufacturers is important due to the consumption of natural resources in their manufacturing processes. Of equal or greater importance are the products they produce and these products’ impacts during their use phase and their EOL phase. Manufacturers control the design of their products, and hence have a role to play in monitoring their consumption of natural resources and their polluting inputs into the environment. Manufacturers are under pressure to ensure their manufacturing processes and their end products are environmentally sustainable as stricter legislation is in constant implementation across most jurisdictions (e.g., EOL Vehicle, Waste Electrical and Electronic Equipment WEEE, Restriction of Hazardous Substances RoHS directives). Additional expectations are placed on manufacturers by consumers who expect greener products and by environmentalists who want more environmental friendly products and less polluting manufacturing practices. The reaction of the public to industrial pollution has both immediate and enduring financial and public
relations consequences. For example, British Petroleum (BP) dropped from being the second to fourth largest oil producer during and after the Gulf of Mexico oil spill crisis. Increasing competition among manufacturers also encourages viewing the creation of environmentally sustainable products as a business opportunity rather than a burden. Manufacturers have the option to improve their performance in conserving natural resources. This includes the adoption of more energy efficient technologies in their manufacturing processes, and this is now a trend in today’s industries. Manufacturers are continuously improving their manufacturing processes to maximize the utilization of their input materials and reduce environmental pollution.

This research project recognizes the need to address environmental benefits and resource saving in remanufacturing. It focuses on the remanufacturing of products categorized as energy-intensive products (EIPs) with a case study of ACs as an example to demonstrate the implementation of the proposed methodology.

This chapter presents a review of related literature. The review aims at identifying developments in remanufacturing theories and practices. The main focus of the review is the environmental performance of remanufacturing. In section 3.2 the concept of product life cycle with a closed loop is reviewed. Possible recovery options and their hierarchy from an environmental point of view are discussed in section 3.2.2. Input, output, control, and mechanisms used in remanufacturing are reviewed in section 3.3. The environmental performance of remanufacturing is reviewed in section 3.4. Literature related to the remanufacturing of ACs is surveyed in section 3.5. The chapter concludes with a critical review and an analysis of gaps found within the reviewed literature.

2.2 Product design for a closed-loop life cycle
Product design based on a closed-loop life cycle is proven to be an effective design approach. This approach considers the phases in a product’s life cycle, which comes after the use phase. Traditionally, manufacturers’ responsibility ends once the product finishes its use phase and it is no longer of use to the end user. The new approach aims at closing the loop in the life cycle of products that reach their EOL. Product retirement (recovery options) is the focus of closed-loop design. The major design goals of this approach are designs for reuse, recycle, remanufacture or energy restoration.

Manufacturers’ involvement in closed-loop product design is motivated by improving their public image and reputation, improving their “green” citizenship, and generating profit from in the future recovery of their products. All these benefits can bestow on a manufacturer an advantage over competitors and may eventually increase their profit share.

Products which are designed with a closed-loop life cycle are more suitable for recovery due to ease of disassembly, modularity, parts’ interchangeability, and material recyclability are examples of issues considered during design of products that have a closed-loop life cycle. Recovery of such products has a strong potential for a profit-making business as the resources originally used to produce the retired product are conserved in the recovery process. Additionally, recovered products use less material, energy, and overhead to restore product functionality. Thus, this business is expected to be profitable for business owners and more sustainable for the environment.

2.2.1 End-of-Life product

A succinct and comprehensive definition of a EOL product is laid out in the European Economic Community (EEC) directive on waste that defines an EOL product as “any
substance or object which the holder discards or intends or is required to discard” (Waste Directive 75/442/EEC, 2003). This definition is also adopted by Directive 2000/53/EC to define EOL vehicles. Kiritsis et al. (2003) define EOL product as a product retired from the functional environment due to technical, economic, social, and/or legal reasons. The Waste Directive 75/442/EEC identifies sixteen types of substances and objects to be considered as EOL products. These types of EOL products can be assigned to product life phases shown in Figure 2.1, for example, mining residues or oil field slops are EOL products for the material extraction phase. Machining/finishing residues or off-specification products are EOL product examples of manufacturing phase. Based on the previous definitions and with the aid of closed loop life cycle phases shown in figure 2.1, EOL product can be defined as material or product that does not fulfill the intended purpose of use during any phase of product life cycle.

![Figure 2-1: Types of EOL products related to product life cycle phases.](image)

EOL products contain value that has not been completely restored (Zussman, et al., 1994). Hence, the objective of EOL product recovery is to restore this contained
value. Saman M. et al. (2010) identify three types of values: (1) value contained as energy; (2) value contained in materials; (3) value contained in parts, assemblies, or product. Traditionally, the amount of value restored as energy is less than as material and the material value is less than value contained in parts or products. This general ranking is followed in the recovery process.

2.2.2 Recovery options

There are different terminologies for recovery options. Examples of terms include: resale; reuse; remanufacture; repair; refurbish; reclamation; high grade recycling; low grade recycling; incineration; scrap; and disposal to landfill. A clear distinction between these options is sometimes is difficult to define. This distinction becomes more ambiguous when terminologies used by different industries in their daily activities vary. For example auto recyclers use the term “recycling” to refer to parts in reuse. In the literature, authors have attempted to define and classify recovery options based on particular criteria. Wadhwa et al. (2009) identify five recovery options based on an operational criteria perspective. Based on the degree of required disassembly five recovery options are identified: repair and reuse; refurbishing; remanufacturing; cannibalization; and recycling. Jun et al. (2007) classify recovery options based on recovered input: product; part; material. Within the part level four options are identified: disposal and replacement; reuse; reconditioning; and remanufacturing. Thierry et al. (1995) classify recovery options according to two major criteria i.e., the identity and functionality of EOL product. The repair, refurbishment and remanufacturing options are identified when the product keeps its original identity. Repair is selected when the purpose is to bring the product into a functioning state. Refurbishment’s purpose is to bring functionality to a higher level
than in the repair state. Remanufacturing is to bring the product to an “as new” functionality. If the product loses its identity then recycling and cannibalization are identified. In cannibalization selective components retain their functionality.

Researchers attempt to define recovery options by giving specific criteria for each option instead of giving general criteria that work for all options. Ming et al. (1997) defines the following recovery options: (1) resale: when EOL product is recovered and sold with minimal intervention; (2) remanufacturing: when the EOL product is restored to its functional and cosmetic value similar to its original condition; (3) upgrade: is done on an existing product at the owner’s premises to add new functionality; (4) recycling: is to recover materials and perhaps components; and (5) scrap: when the product is sent to landfill or incineration. A concise definition of remanufacturing is offered by Hauser and Lund (2008) based on twenty years of practical experience in the US remanufacturing business. They define remanufacturing as the process of restoring a non-functional, discarded, traded-in product to as new condition.

In the literature there is no precise definition for recovery options, nor does it exist in practice. It is also clear that the suggested criteria used to identify recovery options are overlapping, depend on the contexts of time, materials, uses, processes, mid- and end-state conditions. For example, a downgraded component could lose its identity while it is recovered for reuse purposes, also in real life practice some refurbished products are at as-new condition with a warranty matches the original equipment manufacturers (OEM) warranty without being considered as a remanufactured product. Ziout (2013) suggests, in response to these overlapping definitions and conditions, a formal and universal identification system for recovery options.
2.2.2.1 Recovery options hierarchy

Recovery options are prioritized in a manner similar to Lansink’s ladder for waste management, which is followed by European Union (EU) countries. For example, the Environmental Management Act of The Netherlands (2004) prioritizes recovery options as the following: “Recovery through reuse, recovery through recycling, recovery as fuel”. A similar and more detailed hierarchy is suggested by Stevels and Boks (2000). Drawing on an environmental perspective, they prefer the reuse of a product as a whole, then sub-assembly or component, then material recycling to its original application or, if that is not possible, use in a lower application, and then, finally, energy recovery as a direct fuel or as heat to generate electricity. Mazhar et al. (2005) argue that a considerable amount of resources can be saved by avoiding the premature disposal of components. They also argue that substantial manufacturing cost saving can be achieved by shifting material recovery toward component reuse. Nasr and Thurston (2006) as well as Mangun and Thurston (2002) are in agreement with Mazhar et al.

Prioritizing recovery options from an environmental perspective is important. However, it is insufficient. Approaching the issue from a sustainability point of view would be efficient, precise, and comprehensive. When prioritizing recovery options economic, environmental, and societal perspectives need to be considered. Moreover, it has been argued that the reuse of a consumed product is not necessarily better for the environment or resources conservation. New products could be superior in saving energy and may be more efficient in resources utilization compared with a used product. This could outweigh the savings resulting from the reuse of a technologically obsolete product as is demonstrated in the research of Ziout et al. (2011). Their sustainability assessment
approach, using an example of an EOL manufacturing system, shows that the decision is case-dependent and reuse is not always the preferred option in comparison to a new product. The next section provides a model to evaluate reuse of a retired product compared to a new one.

### 2.3 Remanufacturing process

The remanufacturing process is studied from different perspectives. Legislation is considered to be the main starter to initiate the remanufacturing process (Rahimifard et al., 2009). The impact of legislation is clear through EU directives and national legislation. A comprehensive view of the remanufacturing process is shown in figure 2.2 through the IDEF0 diagram that analyses a process from four perspectives: process; inputs; outputs; controls; and mechanisms.

1. **Remanufacturing process input:** The only input of remanufacturing process is the returned flow of EOL products. Quality, quantity, technical characteristics, and timing of returned flow are the major factors to be included.

2. **Remanufacturing process output:** The direct outputs from the remanufacturer’s point of view are the remanufactured product and profit. Indirect outputs are sometimes overlooked. Hula et al. (2003), Lee et al. (2001), and Staikos (2007) count environmental benefits as an output of the remanufacturing process. Societal benefits are considered by Chan (2008), Toffel (2002), and Kiritsis (2003). Compliance with corporate citizenship and improving its reputation are also indirect benefits that should be linked to recovery practices (Matsumoto and Umeda, 2011).

3. **Remanufacturing process controls:** They are factors that govern the process and have influence over its strategic decisions. Leberton (2006) concludes that direct
legislative pressure drives original equipment manufacturer OEM to recover their products when the recovery process is not profitable. Matsumoto and Umeda (2011) consider OEM involvement as a major factor to control and direct the remanufacturing process. Goggin (2000) demonstrates the influence of the supply-demand relationship on the recovery process. The influence of government taxation and incentives are also key factors to consider as they control the remanufacturing process of a certain product within a region.

4. Remanufacturing process mechanisms: Actions that make the process happen and which include: EOL product collection systems and transportation; processing technologies; and distribution channels. Saman et al. (2012) provide a mathematical model to optimize a collection and transportation system for returned EOL product flow. Innovations in remanufacturing technologies have enlarged the feasible space of products that can be suitable for remanufacturing;

Process mechanisms are the operational aspect of the process. They require in-depth consideration from individuals, who are involved in planning and assessing the remanufacturing operation. Once the input product is determined, the decision makers need to decide about the mechanisms of remanufacturing process as they must optimize the value of its output (output product and profit). Direct and indirect outputs are considered in this work as are environmental, societal, and corporate benefits.
A number of remanufacturing definitions are found in the literature. They reflect the complex nature of the process as well as the number of industries and regions that involved with and are developing remanufacturing. Ijomah (2002) offers the following definition that considers consumers’ perspectives and benefits, “The process of returning a used product to at least OEM original performance specification from the customers’ perspective and giving the resultant product a warranty that is at least equal to that of a newly manufactured equivalent.” Hauser and Lund (2003) definition’s focuses on functions and timespan considerations, “Remanufacturing is the process of restoring a non-functional, discarded, or traded-in product to like-new condition, giving the product a second (or third, or fourth) life.” The World Trade Organization (WHO) (2005) offers a definition that can be broadly applied to a number of products and that those products have an principal or essential part(s) can be transformed by processes into a product that either has a new use or can offer the same use of the original and that both types of end products must meet various standards for quality, “Remanufacturing is the generic term that describes the process in which a recovered good, or core, is transformed through cleaning, testing, and other operations into a product that is tested and certified to meet technical and/or safety specifications and has a warranty similar to that of a new
product.” The WHO’s definition acknowledges that, “Different industries sometimes apply other terms, such as refurbishing, reconditioning, or rebuilding, to describe essentially the same process.” Hauser and Lund modify their 2003 definition of remanufacturing to include upgrades and new developments that can be added to the remanufactured product. Hauser and Lund (2008), in consideration of changes brought by both the marketplace and manufacturing standards, offer a new definition when they comment “Remanufacturing is the process of restoring a non-functional, discarded, or traded-in product [at the end of its life] to like-new condition. Both in performance and appearance, the product must meet at least the specifications of the product when new. It may also incorporate upgrades to reflect improvements that have occurred since the product was originally made.” Performance is a feature of the British Standard BS 8887-220 (2010) definition of a remanufactured product as the definition states, “Remanufacturing is the process required to change a used product into an ‘as-new’ product, with at least equivalent performance and warranty of a comparable new replacement product. This remanufacturing process can include parts or components to be used in subsequent assembly.”

It is clear that all definitions of remanufacturing focus on restoring functionality, quality and warranty. Common to these definitions is that the remanufactured product must be equivalent in quality to a new product. In the literature the definitions of remanufacturing are comparable and concise. In industrial practice, however, no such comparability is found. Lund (2012) describes many terms that are used in industry that are equivalent to remanufacturing. Table 2.1 supplies examples of these terms.
Table 2-1: Terms equivalent to remanufacturing

<table>
<thead>
<tr>
<th>Term</th>
<th>Where used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overhaul</td>
<td>Aircraft engines</td>
</tr>
<tr>
<td>Rebuild</td>
<td>Automotive parts</td>
</tr>
<tr>
<td>Recap</td>
<td>Tires</td>
</tr>
<tr>
<td>Recharge</td>
<td>Laser toner cartridges</td>
</tr>
<tr>
<td>Recondition</td>
<td>Wrestling mats</td>
</tr>
<tr>
<td>Remanufacture term</td>
<td>Generic term</td>
</tr>
<tr>
<td>Repair</td>
<td>Industrial valves</td>
</tr>
<tr>
<td>Re-refine</td>
<td>Motor oil</td>
</tr>
<tr>
<td>Restore</td>
<td>Furniture/Musical</td>
</tr>
<tr>
<td>Retread</td>
<td>Tires</td>
</tr>
<tr>
<td>Reset</td>
<td>Military equipment</td>
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</tbody>
</table>


Remanufacturing brings EOL product to ”"Like-new”” status. Remanufacturing involves EOL product collection, disassembly, cleaning, performing manufacturing processes required to bring a used component to like-new status that include reassembly, inspection, and testing the final product. Due to the conservation of value stored in remanufactured products, they are sold at price of 45% to 65% of the product’s new equivalent.(Hauser and Lund, 2003).

Although remanufacturing looks like an appealing option OEMs have reasons not to be involved in remanufacturing. From an OEM point of view, the remanufactured product is seen as a competitor for new products. Also, remanufacturing involves operations that usually are not within the expertise of the OEM. These operations involve risks that many OEMs do not want to take, for example risks associated with running a reverse supply chain. Additionally, many OEMs may not be aware of all of the benefits of the remanufacturing business that make the risk taking justified.

2.4 Environmental performance of remanufacturing
Product recovery aims to divert EOL products from landfill and to utilize them in another use cycle. From an environmental point of view, product reuse is the ultimate recovery option, followed by material recycling and then energy restoration. Product reuse usually involves processes required to restore a specific level of functionality and performance to a product. Remanufacturing, the subject of this research, is one of these processes.

The existence of successful businesses in remanufacturing provides evidence of its economic viability. On the other hand, environmental viability of remanufacturing is questionable for some products. In spite of obvious savings in material and manufacturing processes that would be required if an old product is not retrieved there are environmental impacts that result from remanufacturing processes that could outweigh the possible savings.

There is an established body of literature that explores and demonstrates the environmental savings associated with remanufacturing and other recovery options of products at its EOL. Samples of case studies examined in the literature are discussed in the following section.

2.4.1 Case study of a rear sub-frame in automotive remanufacturing

Rgerich and Homberg (2012) study addresses the environmental benefit of remanufacturing the rear sub-frame in the Volvo V2 program. The frame is made mainly from aluminum, in addition to rubber and steal. The life cycle assessment approach is followed to compare environmental benefits of the remanufactured sub-frame with the new one. Four environmental categories are selected: (1) global warming potential (GWP); (2) photochemical ozone creation potential (POCP); (3) acidification potential (AP); (4) eutrophication potential (EP). The study follows the cradle-to-gate life cycle
assessment approach wherein the comparison is made from material extraction phase until the product leaves the gate of manufacturing plant.

The study concludes that remanufactured sub-frame has less environmental impact based on the chosen four environmental categories. Transportation associated with core collection is the major source of the impacts generated by the remanufactured sub-frame. Extraction of new aluminum and manufacturing processes for the new sub-frame generates most of the environmental impacts. The comparison shows that impacts associated with remanufactured sub-frame are minimal compared to a new product.

2.4.2 Case study of telecommunication networks equipment

The environmental significance of remanufacturing telecommunication networks equipment is studied by Goldey et al. (2010). Two types of equipment are used to conduct the study. The LCA approach is used to analyse the impacts of life phases of this equipment. The use phase is not considered in the analysis due to the fact that both remanufactured and new equipment will have the same impact. The study followed the ISO 1440 methodology and relies on data available both publically and commercially. The assessment is conducted using GaBi software (GaBi), version 4.3. In addition to GWP the study investigated other ten environmental categories and found the GWP of remanufactured equipment is 44% to 35% lesser than the GWP of new equipment. The performance, with respect to the other ten studied categories, is similar in most cases to GWP reduction. Marine aquatic toxicity potential showed slightly fewer savings (up to 20% less than the other categories). Overall the remanufactured equipment are environmentally “cleaner” than their new equivalent.

2.4.3 Case study of alternators in the automotive industry
Remanufacturing sustainability of alternators is studied by Schou et al. (2012). They conduct economic, societal, and environmental analyses. The life cycle assessment approach is used to analyse the environmental impacts of three types of alternators. Twelve environmental categories are used. The abiotic depletion potential (ADP) indicator measures the resources and energy required in remanufacturing. It was found that the use phase dominates the overall life cycle result (99%). This result is understandable and expected as the alternator needs energy, taken from the internal combustion engine running on fossil fuel, to work. The study concluded that most of environmental impacts are associated with use phase. Consequently, remanufactured alternators should be as energy efficient as much as or better than new ones to ensure better environmental performance.

2.4.4 Case studies of diesel engines

The remanufacturing of a diesel engine, in the Chinese truck industry, is the focus of a study by Shi et al. (2015). A life cycle assessment for a new diesel engine and its remanufactured equivalent with an upgrade to liquefied natural gas (LNG) is the subject of the study that shows that the remanufactured LNG engine has less environmental impact than a new equivalent diesel engine. Five environmental categories, shown in table 2.2, are selected to conduct the comparison. The better environmental performance of remanufactured engine results from the reduction of impacts in the use phase.

Lui et al. (2014) implement the cradle-to-gate life cycle assessment approach in assessing the remanufacturing of diesel engine in the automotive industry. Six environmental categories are used to conduct the comparison. The benefit related to environmental impact is with regard to ODP, which is reduced by 97%, followed by EP.
GWP, POCP, AP, and ADP, which can be reduced by 79%, 67%, 32%, and 32%, respectively. The study does not comment on why the use phase is not included in the assessment.

2.4.5 Case study of home appliances

Boustani (2010) quantifies the cumulative energy demands of remanufactured home appliance products (dishwasher, refrigerator, and clothes washer) during their life cycles and compares them to their equivalent in new products. The study uses the life cycle approach to conduct the comparison. The study concludes that from a total life cycle perspective, remanufacturing may be a net energy-loss option. This is due to the dominance of the use phase in energy consumption throughout the life cycle of the investigated products. The energy consumption of home appliances during their use phase is improving over time with new appliances using less energy than remanufactured ones.

Table 2-2: Literature review of successful remanufacturing cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Methodology</th>
<th>Tools</th>
<th>Source of data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telecommunication networks equipment: Goldey et al. (2010)</td>
<td>LCA with indicators: GWP the study investigated 10 environmental categories</td>
<td>GaBi software, version 4.3</td>
<td>PE International (makers of the GaBi software) European Reference Life Cycle Data System</td>
</tr>
<tr>
<td>Alternators in automotive:</td>
<td>Life cycle sustainability assessment (LCSA)</td>
<td>Sustainability dashboard</td>
<td>GaBi 4.0 database</td>
</tr>
<tr>
<td>Study (Year)</td>
<td>Methodology</td>
<td>Environmental Impact Categories</td>
<td>Database Sources</td>
</tr>
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<td>-------------</td>
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</tr>
<tr>
<td>Schou <em>et al.</em> (2012)</td>
<td>Including Environmental LCA, the environmental categories are: ADP, FWAETP, MAETP, EP, HTP, ODP, POCP, TETP, GWP, AP, RAD</td>
<td>GaBi 4</td>
<td>literature</td>
</tr>
<tr>
<td>Case of diesel engine: Shi <em>et al.</em> (2015)</td>
<td>In this LCA study 5 environmental impact categories were assessed: global warming potential (GWP); acidification potential (AP); nutrient enrichment potential (EP); photochemical ozone formation potential (POCP); and primary energy demand (PED). PED includes 3 non-renewable energy resources (coal, crude oil and natural gas).</td>
<td>CML 2000 by Guinée <em>et al.</em> (2002)</td>
<td>Chinese Life Cycle Database and Ecoinvent 2.0 Database</td>
</tr>
<tr>
<td>Case of diesel engine: Lui <em>et al.</em> (2014)</td>
<td>LCA approach is followed, with the following environmental categories: (GWP); (AP); (EP); (ODP); (POCP); (ADP).</td>
<td>Intergovernmental Panel on Climate Change (IPCC), CML 2002 (Guinée <em>et al.</em> 2002) method, and World Meteorological Organization (WMO) methodologies</td>
<td></td>
</tr>
<tr>
<td>Case of home appliances: Boustani (2010)</td>
<td>Life cycle approach with focus on energy consumption</td>
<td>Direct comparison</td>
<td>Literature review, public database, and directly from manufacturers</td>
</tr>
</tbody>
</table>

### 2.5 Remanufacturing of air conditioners

Although the literature is rich in research that covers many aspects of remanufacturing, AC remanufacturing is not fully addressed. The author is not aware of any industrial example of full remanufacturing of AC. In the literature there is research that states it deals with remanufactured AC, but in fact the processes and practices are similar to repairs rather than remanufacturing. Additionally the processes and practices noted herein dealt with remanufacturing of the compressor not the whole AC.
Yanagitani and Kawahara (2000) used the life cycle assessment approach to compare the environmental performance of two different refrigerators that go in residential AC. In this study the authors compare AC model HCFC22 (R22) to AC model HFC410A. The study finds the HFC (R410) has less ozone depletion potential along with a slight reduction in contributions to global warming potential. Also HFCR410A is found to be more energy efficient than the R22 at certain operating temperatures.

The literature lacks studies that analyse the performance of AC remanufacturing. Although the focus of this study is on environmental performance other aspects of AC performance are not found in literature nor were studies that address the economic, technical, or societal aspects of AC remanufacturing.
3 CASE STUDY BACKGROUND

3.1 Introduction

This chapter clarifies the background of the case study discussed in this thesis. It highlights the uniqueness of the conditions that apply to the studied product in the selected geographical region. Air conditioners (AC) require electrical energy to perform their intended function. AC efficiency is a key factor for saving energy. Users who live in countries where energy use is costly pay more attention to energy consumed by their electrical equipment. Users who live in countries characterized by low energy costs have no motivation to ensure that the energy consumed by their electrical equipment is minimized. Their concern would focus, instead, on environmental issue such as sustainability.

The characteristics of Saudi Arabia, where this case study is conducted, make the study unique. Saudi Arabia is characterized by the one of the hottest region in the world, the country is mainly desert. The country is one of the largest producers of oil in the world and all of the utilities and energy requirements of the country are subsidized by the Saudi government. The Saudi government’s Standards, Metrology and Quality Organization (SASO) imposes energy efficiency regulations on AC manufactured and imported to Saudi Arabia. This ensures that a baseline of energy efficiency is standard for ACs used in Saudi Arabia. These factors all contribute to making AC affordable, a necessity, uniform in energy standards, and ensures widespread use of AC, which in turn contributes to AC being a major source of energy consumption in the country. This combination of factors makes the study’s location unique.
Maintaining AC at the highest level of energy efficiency is an interest of the government interest. The SASO is also considering future legislations for imposing an end-of-life retirement plan for AC. The work conducted in this research paper is part of a larger research project aimed at comprehensive evaluation of AC remanufacturing opportunity.

A local AC manufacturer is a partner in this research study. Their current design of AC is the subject of this case study. The results will help them assess remanufacturing opportunities for their AC. The company produces 700,000 window-mount AC annually. This production goes to local, regional, and some international markets. Eighty per cent of the production is sold to consumers in Saudi Arabia.

3.2 Product background

The product of the study is window-mount air conditioner. Air conditioners are used in hot weather to cool spaces where a controlled temperature provides comfort for people, preserves food stuffs, and enables the consistent operation of technology and machinery. Electric energy is used to perform this task. Air conditioners are characterized by a high level of energy consumption during their use phase. The consumed energy is allocated to two electric motors: one that drives a compressor for compressing the refrigerant, and a second motor which drives fans to blow air that perform a heat exchange role in the refrigeration cycle. Air conditioners use a reverse Carnot cycle to cool the air. Figure 3.1 demonstrates the refrigeration cycle employed in window-mount ACs. Refrigerant is a mixture of gases that undergo phase changes during the refrigeration cycle. Refrigerants are selected based on the intended application, their thermal properties, and their impact.
on human and environment health. The product under the study uses Refrigerant R22 in its cooling cycle. R22 is a hydrochlorofluorocarbon (HCFC) compound, the chlorine content is a ozone-depletion gas. Many countries’ regulations phased out its use in the air conditioning industry due to its impact on the environment and in anticipation of future regulations that might ban its use. The industrial partner in this study is planning to phase out the use of R22 and replace it by R410-A in the near future.

**Figure 3-1: Window-mount air conditioning refrigeration cycle.**

The subject of this case study is an AC designed to cool a space equivalent to a bedroom size. The primary market for this product is residential. Its secondary market could be offices in small companies where central air conditioning is not used.

The cooling capacities of this type of AC ranges from 18000 BTU to 24000 BTU. The AC utilizes a refrigeration cycle with FREON 22 to perform its intended function. The product is composed of the following assemblies:

1. Electrical control unit: The main function is to control the room temperature, air flow, and modes of operation. This unit is assembled by the local manufacturer.
2. Compressor: The main function is to compress the refrigerant gas and circulate it throughout the whole cycle.

3. Condenser: It works as a heat exchanger. The heat of compressed refrigerant is exchanged into the environment.

4. Evaporator: It exchanges the heat of room air with the cool refrigerant.

5. Air circulation assembly: Provides air flow for both the evaporator and the condenser to facilitate the heat exchange process.

6. Enclosure: It provides a base to assemble all components and a case to protect and contain the AC’s components.

The product of the study is produced by local Air Conditioning manufacturer located in Saudi Arabia. It is the first company in Saudi Arabia specializing in air conditioning. The company has expanded over the past four decades to become a leading international manufacturer of air conditioning systems. It is currently the number one producer of AC in the Middle East and Saudi Arabia. The company designs, manufactures, tests, markets and services a comprehensive range of AC products ranging from compact room ACs and mini split units to large scale central AC, chillers and air handling units for highly specialized commercial and industrial applications.

While the main factory is located Saudi Arabia, the company owns factories in Italy and India. Besides their own brands, they produce AC for several leading international manufacturers under original equipment manufacturer (OEM) agreements. General Electric (GE) is an example. Their production compared to major Saudi Arabian AC manufacturers is shown in figure 3.2.
Figure 3-2: Production of major air conditioner manufacturers in Saudi Arabia. Source: Al-Shaikh (2009).

3.3 Geographical region of the study (Saudi Arabia)

The study is conducted in Saudi Arabia. The country has been the world’s largest oil producers for decades. In addition to oil, natural gas is another source of energy that has been discovered recently in the country. In year 2012 Saudi Arabia was ranked fifth in terms of the world’s largest reserve of natural gas, about 288 trillion cubic feet (worldenergy.org, 2015). The country uses these sources to fulfill its need for energy.

The demand for electricity Saudi Arabia is met by power generated mainly from crude oil and natural gas. Figure 3.3 shows types of fuel used in generating electricity in Saudi Arabia and their contribution to the country’s total electricity production.
Figure 3-3: Type of fuel used in Saudi Arabian electricity production (2013)

Saudi Arabia consumed 256,668 MWh in 2013 (Electricity and Cogeneration Regulatory Authority, 2014). This consumption is dominated by the residential sector as detailed in figure 3.4. Peak consumption occurs in July, particularly in the residential sector, as during this time the temperature in the country is at its peak ranging between 41 to max 53°C (TechSci Research, 2014).

Figure 3-4: Saudi Arabian electricity consumption by sector, 2013
Source: Electricity and Cogeneration Regulatory Authority: 2013 annual report.
Air conditioning contributes to 60% of the total energy consumed by the residential sector (Al-Shalan, 2013), that is 73,920 MWh (256668 x 0.48 x 0.6). This consumption is expected to increase at a rate of 6% annually (Electricity and Cogeneration Regulatory Authority, 2013).

Saudi Arabia has hot and long summers. Temperatures on hot days can reach 50ºC (TechSci Research, 2014). Summer starts in March and lasts until October with temperatures ranging between 39ºC to 45ºC; in some regions the temperature rises up to 50ºC during this time of the year. The highest demand for AC occurs during June.

Figure 3-5: Saudi Arabia’s electricity consumption growth
Note: source of data is Electricity and cogeneration regulatory Authority- 2013 annual report

The number of AC has increased in the country and will continue to increase in the future.

The increase can be attributed to the following factors:

- Hot climate: The arid climate in the central region of the country and the humid climate at the coasts along with high temperatures keep the demand for air conditioning very high.
• Subsidized electricity price: The government of Saudi Arabia subsidizes electricity prices to keep it affordable for all of the country’s population including those in financial need. In 2013, the subsidy was more than 40 billion USD and kept the price for electricity was one of the world’s lowest. (Electricity and Cogeneration Regulatory Authority, 2013)

• Population growth: Demand for air conditioning depends on increases in Saudi Arabia’s population, which is estimated at 2.45% per annum (The National Commercial Bank, 2009).

• Economic growth: The continuous formation of new households, private business enterprises, new governmental and private buildings as well as other governmental and private establishments creates a large demand for AC. Economic growth increases number of the number of expatriates who come to the country to work. This number is estimated at 20% of the population, the number of expatriates contributes to the demand for air conditioning.

• Mega-development projects: These mega-projects, with the substantial financial investments associated with them, are set to increase the demand for air conditioning systems in both commercial as well as residential sectors over the next five to fifteen years (TechSci Research, 2014).

• New energy efficient technologies in air conditioning. Replacement of old systems and emergence of new more efficient and smaller ACs with more diverse functions will remain a main driver for AC demand.
The demand of air conditioning units is among the highest in the Middle East as well as the world, relative to the size of the Saudi Arabian population (The National Commercial Bank, 2009).

3.4 Summary

There are disadvantages for a country that is one of the largest producers of electricity worldwide as the efforts and policies that argue for energy efficiency and alternative clean energy are debatable. Remanufacturing of AC within this social, economic and political context requires close investigation and solid justifications for the resources required. This is true for arguments regarding environmental benefits and resource savings that are argued to result from remanufacturing. Empirical verification of results as well as benefits is critical. Additionally, for the reasons previously noted, marketing these benefits to customers, manufacturers, and governmental regulatory authorities is difficult. It is noted then that:

- Consumers are not persuaded by arguments for energy savings to upgrade their ACs and buy a remanufactured one.

- Manufacturers will be reluctant to be involved in a remanufacturing practice due to unpredictable demand for such items.

- Governmental regulatory authorities have less motivation to force manufacturers to take responsibility for their products at its EOL. Government, as well, does not want to place an extra burden on national industries.
4 METHODOLOGY AND DATA COLLECTION

4.1 Introduction

This chapter describes the methodology followed in this study to address the study’s research questions. It also identifies the sources of data. In sections 4.2.1 to 4.2.5 phases of the methodology are explained. Section 4.2.1 describes the goals, scope, and definitions used in the study. The life cycle inventory phase is explained in section 4.2.2. The environmental impact assessment phase is detailed in section 4.2.3. Finally, the last phase of the methodology is interpretation, which is defined in section 4.2.4.

Data collection and its resources are detailed in section 4.3. The major sources of data are identified in sections 4.3.1 to 4.3.3. Finally, section 4.3.4 explains why the data quality needs to be verified and what techniques can be used to this end.

4.2 Methodology

This research adopts the international standard ISO 14044 - 2006 Life Cycle Assessment (LCA) methodology to perform the life cycle assessment of AC remanufacturing. This standard provides a standardized methodology to assess and understand the environmental impact of a product or systems of products throughout their life cycle (from raw material extraction through production and distribution, to use phase, and finally, recycling or product disposal). The main focus of LCA is to address the environmental aspects (resources consumption and releases into the environment) and quantify their impacts on the environment. LCA methodology consists of four phases (ISO, 2006): (1) Goal and scope definition phase; (2) Inventory analysis phase; (3) Impact assessment phase; and (4) Interpretation phase. The scope, including the system’s
boundary and level of detail, of an LCA depends on the subject and the intended use of the study. The depth and the breadth of LCA can differ considerably depending on the goal of a particular LCA. The life cycle inventory analysis phase (LCI phase) is the second phase of LCA. It is an inventory of input/output data with regard to the system being studied. It involves the collection of the data necessary to meet the goals of the defined study. The life cycle impact assessment phase (LCIA) is the third phase of the LCA. The purpose of LCIA is to provide additional information to help assess a product system’s LCI results so as to better understand their environmental significance.

4.2.1 Goal and scope definition

The goal and scope of the assessment should be clearly defined at the beginning of the process. This study’s goals are defined by the following:

1. The application (product or system of products) to be studied.
2. The purposes of conducting the LCA.
3. The interested parties in the LCA results (audience).
4. Whether the LCA results will be disclosed to the public or not.

The goal of the study can be revised along with the progress of the assessment process. That depends on the findings of the assessment and the progress of the assessment process; data availability as well as the quality might require the goal to be revised.

The scope of LCA defines the following items:

1. The studied product system and its functions.
2. System boundaries; including assumptions and value choices.
3. Types of environmental impacts to be studied.
4. Data and data quality requirements.
5. Types of critical reviews, and reporting requirements.

4.2.2 Life cycle inventory analysis (LCI)

The LCI analysis is concerned with creating an inventory of all the inputs and outputs of every unit’s process included in the defined scope of the product system to be studied. Data is collected through direct measurements, calculation, or estimation. The purpose of the data collected is to quantify the following input/output of the studied system:

1. Energy and material inputs.
2. Product(s), waste, and any co-product(s).
3. Water, soil, and air releases.
4. Other environmental aspects such as noise, radiation, or heat.

Proper identification of LCI can be conducted through the following measures introduced by the ISO 14044 standards, which includes:

- Drawing a process flow diagram that shows the unit processes to be investigated. The interrelationship among these processes should also be reflected in the diagram.
- Describe and detail each unit’s process by showing its inputs and outputs. Factors affecting input/output and their interactions also need to be clarified.
- Identify the operating condition of the studied product/process and its influence on the input/output.
• Specify and list the units used to quantify the data.

• List and describe techniques used to measure, calculate, or estimate data.

The result of this phase is a compiled list of all inputs such as materials and energy and outputs such as emissions of the studied system. Figure 4.1 demonstrates the entire phase of the methodology. Once the data for each phase is identified it is then related to the functional unit. Finally, an inventory of each element is aggregated. Aggregation should not cause a loss of information or an incorrect conclusion. Aggregation can occur only between substances that lead to a similar environmental impact.

System boundaries can be refined by the end of this phase. Exclusion of life cycle phases or unit processes can be done as part of the refining process and would be based on the significance of the phase/unit process. Sensitivity analysis can help with deciding on this exclusion. Similarly, new life cycle phases/unit processes can be added to the system boundaries if the sensitivity analysis shows they are significant.
4.2.3 Life cycle impact assessment (LCIA)

The LCIA links the identified inventory to impact categories according to characterization models that demonstrate the environmental mechanism through which an inventory can lead to a specific impact. For example, Sulfur hexafluoride is around 4 orders of magnitude larger than CO2 with respect to global warming impact. This phase of the methodology is achieved by performing the following tasks:
1. Selection of impact categories that appear relevant to the goal and scope of the assessment. Characterization models and their indicators are selected as well.

2. Classification: Assignment of life cycle inventory to the identified impact categories.

3. Characterization: Calculation of category indicators’ results and summarization of these results coming from different inventory elements.

4. Generating LCIA profile: A compiled list of category indicator results associated with different impact categories. The LCI elements that can cause more than one impact should be assigned carefully.

5. Conducting a sensitivity analysis: Provides an understanding of how much changes in data will affect the LCIA results.

The process of conducting this phase is demonstrated in figure 4.2 below. The process builds on the inventory which is identified in the previous phase. Environmental impact categories are selected based on their relevance to the studied product system. Table 4.1 shows a non-comprehensive list of environmental impact categories and their indicators.

![Figure 4-2: Life cycle impact assessment process.](image)

The selected impact categories, indicators, and characterization models should be internationally accepted and approved by a recognized and authorized industry association or government department. The scientific and technical validity should also
be maintained. Characterization models should describe environmental mechanisms that can be empirically reproduced.

Table 4-1: Non-comprehensive list of environmental impact categories and their indicators

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Indicator measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resources</td>
<td>kg scarce resources</td>
</tr>
<tr>
<td>Water</td>
<td>m³ water</td>
</tr>
<tr>
<td>Global warming</td>
<td>kg CO₂ equivalents</td>
</tr>
<tr>
<td>Ozone depletion</td>
<td>CFC 11 equivalents</td>
</tr>
<tr>
<td>Acidification</td>
<td>kg SO₂ equivalents</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>kg PO₄³⁻ equivalents</td>
</tr>
<tr>
<td>Smog formation</td>
<td>kg Ethene equivalents</td>
</tr>
<tr>
<td>Waste</td>
<td>kg waste</td>
</tr>
<tr>
<td>Land use</td>
<td>Equivalent hectares</td>
</tr>
<tr>
<td>Abiotic depletion potential</td>
<td></td>
</tr>
<tr>
<td>Photochemical ozone creation potential</td>
<td></td>
</tr>
<tr>
<td>Radioactive radiation</td>
<td></td>
</tr>
<tr>
<td>Terrestrial ecotoxicity potential</td>
<td></td>
</tr>
</tbody>
</table>

4.2.4 Life cycle interpretation

Interpretation is intended to translate the number and figure results from LCI and LCIA into meaningful, logical and easy to understand conclusions. The interpretation phase consists of the following tasks:

1. Identification of significant issues. In this phase of LCA focus can be drawn at the issues found in:
   - Inventory data, such as significant emissions, waste of discharge.
   - Impact categories; significant impacts can be highlighted.
   - Identification of life cycle phases that significantly contribute to LCI or LCA.

2. Evaluation of completeness of data and methods as well as the sensitivity of the results.
3. Drawing conclusions and recommendations that fall within the interest of parties who have interest in the study. Conclusions should be the logical consequence of the results and sensitivity analysis. The conclusions should consider the goal, scope, data quality, and assumptions made in the study.

The interpretation phase demonstrates the iterative nature of LCA. The results of evaluation tasks are introduced to the goal and scope definition, LCI, and LCIA. This feedback could change any of these phases. Figure 4.3 demonstrates this relationship.

![Life cycle assessment framework](image)

**Figure 4-3:** Relationship among elements within interpretation phase with the other phases in LCA (Modified after ISO, 2006).

4.3 Data collection

4.3.1 Verification of data quality
To verify the quality of the collected data, techniques such as mass balance and energy balance are conducted whenever it is appropriate. Data quality should be specified in terms of:

- Collection from specific sites versus general data.
- Being measured, calculated or estimated.
- Precision, as a measure of the variability of the data values for each data category expressed (e.g., variance).
- Completeness, as a percentage of locations reporting primary data from the potential locations.
- Representativeness, as a qualitative assessment of the degree to which the dataset reflects the true population of interest (i.e., geographical, time period, and technology).
- Consistency, as a qualitative assessment of the degree of uniformity with which the study methodology is applied to the study serving as the data source.
- Reproducibility, as a qualitative assessment of the extent to which information about the methodology and data values allows an independent practitioner to reproduce the results reported in the study serving as the data source.
- Justification of the choice of data sources selected in relation to the goal of the study and particularly to scope issues such as temporal, geographical and technology coverage.
- Reliability of different data sources in qualitative terms.
- Completeness of the data provided (for instance, if there are unreported emissions).
• Correctness of the mass and energy balances.
• Agreement between the data sources used and other data sources.

4.3.2 Measured data
Measured data are taken from the industrial partner plant as well as from reverse engineering analyses and measurements conducted in product design lab in the Industrial engineering department at King Saud University (KSU).

4.3.3 Calculated data
Data are calculated or directly collected from published literature or public databases.

4.3.4 Estimated data
Whenever data cannot be measured or calculated an expert estimation is sought from subject matter specialists.
5 DESIGN OF AC REMANUFACTURING PROCESS

5.1 Introduction

This chapter describes the remanufacturing process for the product at hand, remanufacturing process for AC window-mount type is detailed. The designed process here follows the general form of remanufacturing process based on the standard definition of remanufacturing, which is found in BS 8887-220 (2010).

This chapter comes in three sections, the first section introduces the remanufacturing process in general, and identify the specific steps in AC remanufacturing process. Section two details the remanufacturing process of the product in this study. The following operations are identified: Collection operation, remanufacturing operation, and Packaging and distribution. Each operation is detailed further in its corresponding subsection. Last section, section three, summarizes the chapter and establishes links to the next chapter, where inventory of new and remanufactured AC is evaluated.

5.2 Window-mount AC remanufacturing process

Currently there is no existing plant that produces remanufactured AC. The remanufacturing plant, designed in this research is based on standard definition in literature and input from industrial partner. Note that the steps of the remanufacturing process are well-defined both in the literature and the industry. The BS 8887-220 (2010) definition as well as definitions from other studies (see section 2.3) is adopted to identify the required steps in remanufacturing an EOL AC. Discussion with the industrial partner helped in deciding on process parameters. It also clarified ambiguities and helped to choose among alternatives. The life cycle phases of remanufactured AC are shown in
Figure 5.1. The process starts with EOL AC collection, then the collected products are disassembled into separate components. The disassembled components go through a thorough cleaning process that brings components back to its ‘as-new’ state. Each component is tested individually before it is reassembled into the final reassembly. During reassembly, worn and failed components are replaced by new ones. The reassembled unit goes through testing, and a packaging process similar to the process done for a new AC. Storage and distribution of remanufactured AC is identical to the new AC. The following subsections explain the identified steps in AC remanufacturing. The process’s parameters and assumptions are listed along each step wherever these assumptions are made.

![Remanufacturing process of AC](image)

**Figure 5-1: remanufacturing process of AC**

### 5.2.1 Core Collection

The EOL AC are collected from a drop off point (collection centres) that cover the whole geographical area of the studied country. The collection process uses a road transportation method to deliver the collected items to the remanufacturing plant. The
remanufacturer has the choice to select specific locations to be covered by its collection network, and this decision could be either economically or environmentally driven. Collection from a distant location could lead to an increase in environmental impacts due to emissions during transportation of long distances between the collection centre and remanufacturing plant.

This process could also include preliminary inspection and testing. The product goes through three inspection stages before it is accepted for remanufacturing. The three different inspection stages are as follows: (1) Visual inspection; (2) Leaks and rust inspection; (3) operation inspection.

In the first stage, visual inspection is conducted. All of the initial observations are noted and written down. In this procedure the decision of whether the unit is good enough for remanufacturing or not is based on the opinion of the inspector. Units with the least amount of damage are selected for further remanufacturing processes. In the second stage, the inspection is more specific as it looks for specific defects, that are leaks and/or rust. The check for leaks at this phase is done through visual inspection (sometimes when there is a leak, oil residuals might accumulate around the leakage point). Lastly, in the third stage, units are put under usual operational conditions where they are actually plugged into a power source and put to work. In this phase the soundness of the unit is judged by the inspector based on how well is the unit functioning.

When considering the design parameters and assumptions there must be a determination of the process’s parameters and of the collected data. Collection of the units is done using trucks that run on diesel from major cities in KSA where there is the largest number of AC users in the country. The remanufacturing plant is assumed to be in Dammam city.
where currently new AC are manufactured. Table 5.1 shows the transportation distances between major cities from which ACs are collected to where they would be delivered at the remanufacturing plant. Distances have been obtained from Google Maps. The number of expected EOL AC units is estimated based on the population density of each city. The number is calculated by taking the city’s population times a ratio defined as:

\[
\text{Ratio} = \frac{\text{Number of AC unit in use in 2010}}{\text{KSA 2010 population}}
\]

\[= \frac{3.3 \text{ million}}{27 \text{ million}} = 0.122\]

The weighted average is used to calculate the average distance travelled by a unit of collected AC. It is found to be 845.3 km per collected unit.

**Table 5-1: Distances between major KSA cities and remanufacturing plant**

<table>
<thead>
<tr>
<th>City</th>
<th>Distance in km</th>
<th>Population in millions</th>
<th>AC unit in millions</th>
<th>Unit . distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mecca</td>
<td>391</td>
<td>5.18</td>
<td>0.633111</td>
<td>247546444.4</td>
</tr>
<tr>
<td>Riyadh</td>
<td>1,370</td>
<td>3.43</td>
<td>0.419222</td>
<td>574334444.4</td>
</tr>
<tr>
<td>Abha</td>
<td>1,281</td>
<td>1.53</td>
<td>0.187</td>
<td>239547000.0</td>
</tr>
<tr>
<td>Jeddah</td>
<td>1,237</td>
<td>1.1</td>
<td>0.134444</td>
<td>166307777.8</td>
</tr>
<tr>
<td>Dammam</td>
<td>50</td>
<td>0.9</td>
<td>0.11</td>
<td>5500000.0</td>
</tr>
<tr>
<td>Jizan</td>
<td>182</td>
<td>0.66</td>
<td>0.080667</td>
<td>14681333.33</td>
</tr>
<tr>
<td>Madinah</td>
<td>1,180</td>
<td>0.57</td>
<td>0.069667</td>
<td>822066666.67</td>
</tr>
<tr>
<td>Tabuk</td>
<td>1,667</td>
<td>0.51</td>
<td>0.062333</td>
<td>1039096666.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>1.696444</strong></td>
<td><strong>1434033333.0</strong></td>
</tr>
</tbody>
</table>

*Weighted average distance = 845.3 km*
5.2.2 Remanufacturing operations:

Disassembly:
The disassembly of the AC units is executed through several steps, as follows:

• Disassembly of the upper case.
• Evacuation and recovery of the refrigerant.
• Disassembly of the condenser and evaporator.
• Disassembly of the front electrical panel.
• Disassembly of the fan and motor.
• Disassembly of the compressor.

The disassembly flow of the units proceeds in the same order as mentioned above. The following is a description of the process. The process starts with disassembly and the removal of the upper case of the unit. The process requires unscrewing different type of screws that fasten the case to the base and other frontal parts; this involves the use of various hand tools. Second, the refrigerant, which is running in the AC unit, is recovered. It is collected in safe containers according to the regulation and keeping in mind the environmentally friendly procedures. The collected refrigerant can also be used to charge the remanufactured unit as long as the regulations allow for the use of R22 refrigerant.

Thirdly, the condenser and evaporator are disassembled from the base. Through this process, the pipes connecting them with the compressor need to be cut off manually using a handsaw or with the aid of a power tool such as an angle grinder (see figure 5-2). Next, the front electrical panel is disassembled. In the following stage the motor and both fans
are disassembled. Finally, the disassembly process of the AC concludes with the disassembly of the compressor.

During the disassembly process some difficulties might arise due to unforeseen circumstances. For example, some screws could be rusty and thus hard to untighten. Thus the use of lubricant would be needed to untighten it. Destructive disassembly also might be used in some cases.

The majority of the disassembly steps are conducted manually. However at some steps machines/tools are needed. The assumptions for the disassembly are as follows:

• Angle grinder tool of rated power 1000 watt is used to cut the piping or any other rusty parts.

• Hand held power screw driver of rated power 1000 watt is used to unscrew screws that fasten the case to the base and other parts.

• Cutting time using angle grinder is measured to be 5 minutes. This is enough time to release all pipes connections.

• Unscrewing task is measured to be 30 minutes for the studied product. High variation in unscrewing time is expected.

• The total electrical power consumption is calculated as summation of power needed for unscrewing (30 minutes $\times \frac{1\text{ hour}}{60 \text{ minutes}} \times 100 \text{ W} = 500\text{Wh})$ and pipe cutting (5 minutes $\times \frac{1\text{ hour}}{60 \text{ minutes}} \times 100 \text{ W} = 83\text{Wh})$. The total consumed energy per unit AC is 583 (watt.hour)

• Unwanted parts are scrapped according to environmental regulations and guidelines. They go through material recycling. Its environmental impact is not considered in this study as the process is out of the remanufacturer’s control.
Cleaning

Due to the extensive usage of the units over a long span of time there is an accumulation of dirt and biological matter on various parts of the AC unit, and thus cleaning of the soiled parts is imperative. (See figure 5-3). The following is a description of the cleaning process. AC parts during the cleaning process go through consecutive steps to reach the desired cleanliness level, as shown in figure 5.16. During the cleaning process, AC parts are put on a conveyor and are then moved to the various cleaning sections. In the first stage, all parts are cleaned by compressed air at high pressure (7 bar) to remove the accumulation of dust and solid matter. The second phase is cleaning of parts with hot steam wherein steam is blasted on the parts to clean them. Lastly, all parts are dried using compressed air, so that they are ready for the next step.
Cleaning involves the use of electricity, desalinated water, and natural gas as a source for heating the water and producing steam. The output is mainly cleaned parts ready for testing and reassembly. Steam cleaning produces waste water that can be directly connected to municipal sewage system for further treatment.

![Figure 5-3: Examples of dusty and oily parts](image)

The design parameters and assumptions of this stage involve, as mentioned earlier in the previous section, the cleaning process. This is executed on each separate part of the remanufactured AC. The following provide the details of each stage of the cleaning process, along with the assumptions regarding each single stage. Figure 5-4 shows the flow of the cleaning process.

1. **Compressed air cleaning:**

   In this stage the parts are cleaned with compressed air that flows on a relatively high speed to clean off residual dust or sand. In order to have the optimum cleaning in this case the following elements must be incorporated:

   - The air is compressed to 7 bar.
   - The pipe used has a diameter of 10 mm.
   - Air flow is 4.2 m/s (recommended optimum speed).
   - Flow rate is calculated through \( Q = \frac{60\pi d^2 V}{4} = 0.1387 \text{ Nominal m}^3/\text{s} \).
• Energy consumption is calculated (0.059 MJ), based on energy consumption of selected air compressor.

2. Steam cleaning

In this stage the parts are washed using steam to get rid of any residuals of dirt and mud.

The process design parameters and assumptions are as follows:
• A pump of a power rating of 7.5 kW providing a flow rate of 1000 l/h is used.
• Parts of each AC unit require 5 minutes cleaning time with steam.
• Power consumption is 0.625 kW.

3. Drying using compressed air

After the units pass through steam cleaning they are dried using compressed air. The assumptions in this case are similar to that in the first step (i.e., compressed air cleaning) except for the amount of air and energy, in this case they are doubled to become 0.118MJ, and 0.277 Nm$^3$, respectively.

5. Material handling

In order to move each part from one place to another, conveyor is used for this purpose. It is assumed to be motorized thus satisfying mass production demand.

The assumptions for the material handling throughout the processes are as shown below:
• The cleaning stages are separated by a distance of 5 m.
• 4 conveyors are used, 5 m long.
• The conveyors are running on 1 hp motor and provide a speed of 0.2032 m/s for each unit.
• Energy consumption is calculated (0.07345 MJ).

**Figure 5-4: Processes of cleaning phase.**

**Reassembly**

The following section presents the description of the reassembly phase. This phase starts by verifying the quality of recovered parts. Both inspection and testing are done on all parts before they are placed in reassembly. Once the parts pass the inspection process they then go on to the next steps in the reassembly phase. Failed parts as well as parts that need extensive repair are replaced with new ones. Figure 5-5 demonstrates the reassembly steps. In this stage of the remanufacturing of an AC the following steps are followed to reassemble the AC back into a functional unit, they are:

1. Assembly of evaporator and condenser to the base.
2. Assembly of motor and fans.
3. Assembly of compressor.
4. Brazing of pipes and joints.
5. Assembly of front electrical panel along with wiring.
6. Refrigerant charging.
Figure 5-5: Processes of reassembly phase

It is important to note that all parts are assembled with the base (i.e., parts themselves were not disassembled—they were treated as one unit). Also, as the dimensions and sizes of the units are different due to different types of ACs the assembly process is done manually with the aid of power tools. These tools are different than those used for the new AC. Tools that are necessary to finish the reassembly include:

- Welding tools (brazing).
- Refrigerant injection tool.

All parts are moved from one stage to another using an electrical roller conveyor. Brazing tools are used to weld the pipes together as well as joints that were cut during the disassembly process. An example of the tools needed for that can include a liquefied petroleum gas (LPG) welding kit. A refrigerant charging method similar to the one used in manufacturing new AC can be used in the case of remanufacturing. Lastly, a roller conveyor is needed to facilitate the moving of units after they are assembled since the process is manual.
The design parameters and assumptions for this stage, after the parts are cleaned they are put together to be ready to be sold again, all of the parts need to be inspected and tested as is discussed in the following section:

- Visual inspection, wherein the inspector visually investigates each component for apparent damage, crack or inconsistency. This inspection requires no electricity or input materials.

- Leak test: In addition to the visual testing, a pressure test is performed for all components of the AC including: Compressor, evaporator condenser, and pipes.

Reassembly can be facilitated using a power screwdriver. The same type of powered screwdriver used in the disassembly is used for reassembly, hence same design parameters and assumptions apply.

In the brazing process LPF is used as a source of heat to heat the copper pipes and to melt the brazing rod. Due to large heat losses inherent in the process, the calculated energy for copper pipe heating and the brazing rod melting is very low compared to the losses. The total energy expended would be estimated based on an expert’s judgement. It is estimated at 0.001 MJ.

In the stage of refrigerant charging an R22 refrigerant is charged to the unit. The unit is connected to a reservoir of R22 at a particular pressure. Charging lasts until pressure in the reservoir and the AC unit become equal. The studied model requires 1 kg of refrigerant. In case of a new type of refrigerant is used, the charged mass need to be determined.

For the final inspection the final assembled unit is tested to verify its functionality and to ensure it is free of any defects. The unit is tested under its normal working condition. In
this test, the installed compressor of the AC itself performs the job. It will compress and circulate the refrigerant throughout the unit. The consumed electricity depends on the compressor power rating, which in this case has a power rating of 1.75 kW. The pressure test is run approximately for 330 second and so the power consumption is 0.16 kWh. During the test R22 detector is manually used to detect any leak in the whole system.

5.2.3 Packaging and distribution

Once the AC unit passes the final inspection, it moves to the packaging station. The purpose of this stage is pack the AC unit so that it can be shipped for the storage or directly to the showrooms. Packaging station uses cardboard boxes and polystyrene as packaging materials. The process is semi-automated. The cardboard boxes come with the polystyrene base located in the bottom of the box, this process is done manually. Semi-automated arm picks the AC unit and inserts it in the box, closing and sealing the box is done automatically using a packaging machine.

Palletization is done manually, four units are stacked on one pallet, then moved to the finished good storage using forklift. The packaging stage for remanufactured AC units is the same as for new ones. Hence, no need to conduct LCI assessment for this stage. Similarly, storage and distribution phase are identical for both remanufactured and new AC units and LCI assessment is also not needed.

5.3 Summary

Remanufacturing process for AC window-mount type is designed in this chapter. Standard form of remanufacturing process is followed; the remanufacturing process of
AC has all processes and operations found in the standard form. The process has collection operation, remanufacturing operations that include disassembly, cleaning, reprocessing, testing and reassembly. Finally the reassembled product goes through packaging and distribution process, which is exact same variant as in new AC. Hence, the design for packaging and distribution for new AC can be utilized for remanufactured one. The process documented in this chapter is used to identify the environmental inventory for remanufacturing phase in the product lifecycle.
6 LIFE CYCLE ASSESSMENT

6.1 Introduction

This chapter provides the pre-requirement of conducting LCIA. In the next section the scope and goal of the study are defined. In the remaining sections, the LCI of a new AC and remanufactured AC are detailed.

6.2 Goal and scope of the study

6.2.1 Goal of the study

The goal of the study is to verify the environmental benefit of remanufacturing air conditioners. The study aims to investigate if the remanufactured AC has fewer environmental impacts than an equivalent new AC. The study is conducted for academic research purposes. However, it can be used by the industrial partner and governmental legislators can use it as a guide in their decision making process. Public disclosure is not a goal of this study.

6.2.2 Scope of the study

The scope of the study is defined by the following research questions:

- Does the remanufactured AC have less environmental impact than its equivalent in a new AC, considering the overall life cycle?
- What are the environmental impacts of the remanufactured AC?
- What are the environmental impacts of the new manufactured AC?

The following is established to define the scope of the LCA study, so that the above mentioned research questions can be answered.

1. The studied product system and its functions:
The product system of the study consists of a new AC that has cooling capacity of 18,000 British Thermal Unit (BTU). The second product is a hypothetical remanufactured AC of the same type by the same manufacturer. The main function of the studied product is room air cooling during hot days of the year. Another, minor, function is room air heating during cold days of the year. The second function will not be included in this study since it is rarely needed in the geographical region where the study is conducted.

2. System boundaries, including assumptions and value choices:

The life cycle assessment includes the entire phases of the life cycle of the remanufactured and new AC, with the exception of phases and processes which are identical in both products as seen in figure 6.1. The reason for not including these phases is the goal of the study which is to compare the two ACs and verify if the remanufactured AC has less of an environmental impacts than the new one. Impacts of identical phases will be canceled out during the comparison. Hence, there is no reason for including identical phases/processes that the remanufactured and new product have both been exposed to.

Typical life cycle of new product starts at material acquisition, it then proceeds to manufacturing, assembly, packaging, distribution, use, and disposal. At the disposal phase, many options are available (reuse, recycle, landfill). For the studied product, reuse and recycle are the common disposal options. Reuse is common when the product is functioning, while recycling is common when the product is not functioning. Material recyclers always looking for a retired AC due to its scrap value, mainly due to the aluminum and copper content
Typical life cycle of remanufactured products starts from core collection, remanufacturing (inspection and sorting, disassembly, parts processing, testing), assembly, packaging, distribution, use, and disposal. At the disposal phase ideally only one option is available, which is remanufacturing. It is at the end user’s choice to put the retired product back in the remanufacturing channel. The assumption is made here that the product will go into the remanufacturing channel. This assumption is not far from reality, because the remanufacturing program should have incentives that attract the users to put their EOL product back in remanufacturing channel.

Figure 6-1: System boundaries and life cycle phases of remanufactured and new AC.

3. Types of environmental impacts to be studied:
Resources utilization is the main driver for remanufacturing, thus energy and martial consumption is the environmental category that requires the most attention. Research by Yanagitani and Kawahara (2000) suggests that the research should focus on three impacts most closely associated with AC, it includes: global warming; ozone depletion (as FREON R22 and HCFC22 cause OD); and industrial waste.

Kleine (2009) uses global warming gas emissions and energy consumption in his model to find out the optimal replacement life for a central AC. In this study the following universally accepted impacts are studied. The scientific models and mechanisms that relate these impacts to their causes are well-established, the impacts are:

1. Acidification potential. (AP)
2. Eutrophication potential. (EP)
3. Global warming potential. (GWP)
4. Ozone depletion potential. (ODP)
5. Photochemical ozone creation potential. (POCP)

The assessment of these impacts is limited to the availability of a scientific model that relates the impact to its causes, also it is limited to availability of software that can perform the analysis.

4. Data and data quality requirements:
The following approach is followed to maintain the data quality; data is sought to be through direct measurement of existing operations or product, if direct measurement is not possible, then data are obtained from technical reports, otherwise is estimated through experts.
5. Types of critical reviews, and reporting requirements:

Critical review required by ISO 14044 standards is not applicable in this study, since it is for academic purposes only and not for public disclosure where a critical review by a third party is required.

6.3 Life cycle inventory analysis (LCI Analysis)

In this section the life cycle inventory of both a new AC and remanufactured AC is conducted. All of the life cycle phases that are identified in the study scope are studied, their inputs and outputs are determined. The LCI of new AC is determined in section 6.3.1, while LCI of a remanufactured AC is discussed in section 6.3.2.

6.3.1 Life cycle inventory of new AC

The life cycle phases of a new AC are demonstrated in figure 6.2. The life of new AC starts from material processing and goes through manufacturing and assembly. Distribution to retailers and shopping stores, use, and finally disposal are the end phases of a new AC. The inventory analysis will not include the packaging, distribution and disposal phases; since these phases are identical for both the new and the remanufactured ACs, their environmental impact is identical. Thus there is benefit to conduct a comparison between them (comparison between the two products is the goal of the study).
6.3.1.1 Material processing phase

The environmental inventory associated with material processing phase for any product depends on the materials included in that product. A bill of material and material analysis is a pre-requisite for identifying the inventory of this phase. An AC unit of 2007 model is analysed through reverse engineering in a product design lab at King Saud University, Riyadh, KSA (see Appendix 6.1). The results of the analysis are shown in table 6.1 illustrating the assemblies, components, materials, and the weight of each material. The total mass of each identified material is summarized in table 6.2; The environmental inventory associated with production of these materials is gathered from GaBi Software database that depends on verified databases, it could be public databases, published literature, or purchased databases. Databases such as the US LCI database and the ELCD (European Life Cycle Database) are the main sources for the LCI and LCIA data and information. Four major materials make the total mass of the AC: aluminum, copper, steel, and plastic. Below is the LCI of the production of each of these materials.

![Figure 6-2: Life phases of new AC.](image)

Table 6-1: Material analysis of the studied AC unit — Zamil Model (2007)

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Item</th>
<th>Material</th>
<th>Quantity</th>
<th>Unit</th>
<th>Comments</th>
</tr>
</thead>
</table>

63
<table>
<thead>
<tr>
<th>Component</th>
<th>Material 1</th>
<th>Material 2</th>
<th>Weight</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enclosure</td>
<td>Case</td>
<td>Steel</td>
<td>2 kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td>Steel</td>
<td>2.5 kg</td>
<td></td>
</tr>
<tr>
<td>Condenser</td>
<td>Copper pipes</td>
<td>Copper</td>
<td>4.1 kg</td>
<td>Based on estimated 50% copper percentage by weight</td>
</tr>
<tr>
<td></td>
<td>Aluminum fins</td>
<td>Aluminum</td>
<td>4.1 kg</td>
<td></td>
</tr>
<tr>
<td>Evaporator</td>
<td>Copper pipes</td>
<td>Copper</td>
<td>3.8 kg</td>
<td>Based on estimated 50% copper percentage by weight</td>
</tr>
<tr>
<td></td>
<td>Aluminum fins</td>
<td>Aluminum</td>
<td>3.8 kg</td>
<td></td>
</tr>
<tr>
<td>Compressor: Rotary compressor R22 220V</td>
<td>Case</td>
<td>Steel</td>
<td>5.4 kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stator</td>
<td>Copper</td>
<td>4.3 kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rotor</td>
<td>Steel</td>
<td>6.2 kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Copper</td>
<td>2.3 kg</td>
<td></td>
</tr>
<tr>
<td>Air circulation assembly</td>
<td>Fans (inner and outer)</td>
<td>White plastic</td>
<td>1.4 kg</td>
<td></td>
</tr>
<tr>
<td>Fan housing</td>
<td>Polypropylene</td>
<td></td>
<td>1.2 kg</td>
<td></td>
</tr>
<tr>
<td>Motor</td>
<td>Case</td>
<td>Steel</td>
<td>0.8 kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Core</td>
<td>Steel</td>
<td>1.3 kg</td>
<td>Based on estimated 50% copper percentage by weight</td>
</tr>
<tr>
<td></td>
<td>Copper</td>
<td>1.3 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Armature</td>
<td>Steel</td>
<td>1.1 kg</td>
<td>Based on estimated 50% copper percentage by weight</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Copper</td>
<td>1.1 kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shaft</td>
<td>Steel</td>
<td>0.4 kg</td>
<td></td>
</tr>
<tr>
<td>Control box</td>
<td>Wires</td>
<td>Copper</td>
<td>0.3 kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Knobs and case</td>
<td>Plastic</td>
<td>0.02 kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PCB</td>
<td>Laminate</td>
<td>0.03 kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Copper</td>
<td>0.001 kg</td>
<td>Estimated based on 165 micron of copper thickness</td>
</tr>
</tbody>
</table>
Table 6-2: Material composition of the studied AC

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass (kg)</th>
<th>Major forms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>7.9</td>
<td>Sheet (0.2 mm)</td>
</tr>
<tr>
<td>Steel</td>
<td>19.2</td>
<td>Sheet (1 mm to 5 mm)</td>
</tr>
<tr>
<td>Copper</td>
<td>17.2</td>
<td>Pipes and wires</td>
</tr>
<tr>
<td>Plastic</td>
<td>2.61</td>
<td>Injection molded plastic</td>
</tr>
<tr>
<td>FREON R22</td>
<td>1.0</td>
<td>Refrigerant gas</td>
</tr>
<tr>
<td>Others</td>
<td>0.03</td>
<td>Laminate</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>47.94</strong></td>
<td><strong>Total weight of the AC</strong></td>
</tr>
</tbody>
</table>

The research established that the LCI of aluminum sheet production has a total mass of aluminum, found in the studied AC, is 7.9 kg. The production process of the aluminum sheet is shown in figure 6.3. The process is based on ELCD from GaBi. The diagram shows the major inputs and outputs of the process. Detailed inventory can be found in GaBi’s professional database.

![Aluminum sheet production](image)

**Figure 6-3: Aluminum sheet production. Modified from ELCD (2015a).**

ELCD data are based on European industry standards, hence the energy mix shown in table 6.3 represents the European aluminum sheet production energy mix. It is important
to note that different geographical regions may have different energy mixes. Aluminum is not produced in KSA, hence European data is used.

Table 6-3 Aluminum production energy mix

<table>
<thead>
<tr>
<th>Source of energy</th>
<th>Energy used per 1000 kg of AL.</th>
<th>Percentage</th>
<th>Energy used per 7.9 kg of aluminum sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas; 44.1 MJ/kg</td>
<td>15172.8</td>
<td>27</td>
<td>119.86512</td>
</tr>
<tr>
<td>Uranium</td>
<td>12429.6</td>
<td>22</td>
<td>98.19384</td>
</tr>
<tr>
<td>Primary energy from hydro power</td>
<td>9993.59</td>
<td>18</td>
<td>78.949361</td>
</tr>
<tr>
<td>Crude oil; 42.3 MJ/kg</td>
<td>8704.34</td>
<td>15</td>
<td>68.764286</td>
</tr>
<tr>
<td>Hard coal; 26.3 MJ/kg</td>
<td>7463.41</td>
<td>13</td>
<td>58.960939</td>
</tr>
<tr>
<td>Brown coal; 11.9 MJ/kg</td>
<td>2724.02</td>
<td>5</td>
<td>21.519758</td>
</tr>
<tr>
<td>Primary energy from solar energy</td>
<td>274.878</td>
<td>0</td>
<td>2.1715362</td>
</tr>
<tr>
<td>Primary energy from wind power</td>
<td>132.836</td>
<td>0</td>
<td>1.0494044</td>
</tr>
<tr>
<td>Primary energy from geothermic</td>
<td>26.5823</td>
<td>0</td>
<td>0.21000017</td>
</tr>
<tr>
<td>Peat; 8.4 MJ/kg</td>
<td>23.7263</td>
<td>0</td>
<td>0.18743777</td>
</tr>
<tr>
<td>Wood; 14.7 MJ/kg</td>
<td>0.260377</td>
<td>0</td>
<td>0.002056978</td>
</tr>
<tr>
<td>Biomass; 14.7 MJ/kg</td>
<td>0.0000003069</td>
<td>0</td>
<td>2.42E-08</td>
</tr>
<tr>
<td>Total</td>
<td>56946.04298</td>
<td></td>
<td>449.8737395</td>
</tr>
</tbody>
</table>

The total mass of copper found in the studied AC is 17.2 kg. It forms the tube where the refrigerant is circulated. The electric wires are also made of copper. The production of copper wires and tubing goes through the same process as is illustrated in figure 6.4. The process starts by copper mining, pyro metallurgy, semi fabrication, extrusion and finally drawing. The red dotted line in the graph represents the boundaries of the production process; the inputs for the process are natural resources. The outputs are emissions and the final products include: wires, rods, tubes, strips, and sheets. The total energy required to produce the desired quantity (17.2 kg) is summarized in table 6.4.
Figure 6-4 Copper tube production. Source (ELCD, 2015c).

Table 6-4 Energy mix for copper tube production

<table>
<thead>
<tr>
<th>Source of energy</th>
<th>MJ / 1000 kg of copper tube</th>
<th>Percentage</th>
<th>MJ/ 17.2 kg of copper tube</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas; 44.1 MJ/kg</td>
<td>10431.6</td>
<td>27</td>
<td>179.4235</td>
</tr>
<tr>
<td>Uranium</td>
<td>3504.83</td>
<td>22</td>
<td>60.28308</td>
</tr>
<tr>
<td>Hard coal; 26.3 MJ/kg</td>
<td>2989.1</td>
<td>18</td>
<td>51.41252</td>
</tr>
<tr>
<td>Crude oil; 42.3 MJ/kg</td>
<td>1337.24</td>
<td>15</td>
<td>23.00053</td>
</tr>
<tr>
<td>Brown coal; 11.9 MJ/kg</td>
<td>1126.84</td>
<td>13</td>
<td>19.38165</td>
</tr>
<tr>
<td>Hydro power</td>
<td>760.303</td>
<td>5</td>
<td>13.07721</td>
</tr>
<tr>
<td>Wind power</td>
<td>105.341</td>
<td>0</td>
<td>1.811865</td>
</tr>
<tr>
<td>Solar energy</td>
<td>82.1583</td>
<td>0</td>
<td>1.413123</td>
</tr>
<tr>
<td>Geothermic</td>
<td>54.5475</td>
<td>0</td>
<td>0.938217</td>
</tr>
<tr>
<td>Peat; 8.4 MJ/kg</td>
<td>16.219</td>
<td>0</td>
<td>0.278967</td>
</tr>
<tr>
<td>Biomass; 14.7 MJ/kg</td>
<td>0.218587</td>
<td>0</td>
<td>0.00376</td>
</tr>
<tr>
<td>Wood; 14.7 MJ/kg</td>
<td>0.103905</td>
<td>0</td>
<td>0.001787</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>20408.50223</strong></td>
<td><strong>100</strong></td>
<td><strong>351.0262</strong></td>
</tr>
</tbody>
</table>
Natural gas contributes to 50% of the energy used to produce copper. Nuclear energy from uranium and energy from hard coal represent 80% of the total consumed energy in the copper production process. Note that this information is based on European industrial processes and European life cycle databases. Detailed inventory can be found in GaBi’s professional database.

The life cycle inventory of FREON R22 production is also considered in this study. No LCI data is available for the production process of R22 refrigerant. The literature review conducted in this study could not find literature related to environmental impacts of the R22 production process. GaBi software has R22 data as a output flow from a process to air as an emission. This flow will be included in the assembly phase where the refrigerant is charged to the AC unit. Not considering the impact of this process gives the new AC advantage over the remanufactured AC. This influences the decision making process when considering adopting remanufacturing.

The life cycle inventory of plastics production is also considered in this study. It should be noted that the plastic parts found in the AC will not be considered for remanufacturing. The economic and technical analysis shows that remanufacturing of these parts is not feasible. New plastic parts will be included in the remanufactured AC. Hence these parts will be new in both the remanufactured and new AC, thus there is no need to conduct an inventory analysis for them. The goal of the study is to conduct a comparison between the remanufactured AC and the new AC. In the inventory analysis of the parts that go through the same processes in both types of AC will cancel each other out, consequently the following components are excluded from the inventory analysis: (1) fans (inner and outer); (2) fan housing; and (3) knobs and case.
The LCI of material processing phase for new AC is modeled using GaBi as shown in figure 6.5 below. The model reflects not only the production process but also the shipping material from the manufacturer which is from various places in Europe to Dammam port in KSA. The total LCI of the plan, shown in figure 6.5, accounts for the LCI for both production and shipping. It should be noted that it also affects the environmental impacts of this phase.

Figure 6-5: Material processing phase model using GaBi software.

6.3.1.2 Manufacturing phase

The manufacturing processes of AC can differ from manufacturer to another. The level of automation in manufacturing processes depends on the production volume. Since not all manufacturers are large enough to automate their processes, a variation in manufacturing processes is expected. This study is restricted to the manufacturing process followed by the industrial partner, which is demonstrated in figures 6.6 and figure 6.7 showing a Google Street View of the plant’s dimensions. The manufacturing plant is divided into
departments, each department produces parts that are common in their materials; the assembly department assemble all the parts together.

![Diagram of AC manufacturing processes]

**Figure 6-6: Manufacturing processes of AC, based on the Zamil plant.**

The assembly process is analysed in the next section. The LCI analysis includes the department shown in green in figure 6.6, the grey coloured departments are not considered in the analysis since it is held in common with the remanufactured AC unit. The following departments and their processes are assessed.

In the life cycle inventory of raw material storage, a storage area is dedicated for raw material. Storage is not cooled during the summer nor is it heated in the winter. It is lighted and ventilated. Electricity is the only source of energy for light and ventilation. The proper way of allocating energy consumed by lighting and ventilation is through the area of the ventilated space. The allocation steps are as follows:
• Calculate the area of the storage department:

\[ A = 57 \times 77.5 = 4417.5 \text{ m}^2 \]

• Collect the energy intensity (MJ/m\(^2\)/year):

Estimated to be 0.9 MJ/m\(^2\)/year

• Calculate the energy consumed by the storage department area per year:

Energy = Area * energy intensity = 4417 * 0.9 = 3975.3 MJ/year

• Calculate energy per functional unit (one AC):

\[ = 3975.3 \text{ MJ/year} / 70000 \text{ unit} = 0.05679 \text{ MJ per functional unit} = 0.015775 \text{ kWh per functional unit} \]

Note: distances are obtained from the Google maps distance tool as shown in figure 6.7 below.

![Figure 6-7: Google Street View and distances of the Zamil AC manufacturing plant.](image)

When analyzing the life cycle inventory of aluminum fins manufacturing it should be noted that the manufacturing process of aluminum fins starts by unwinding aluminum coil using an unwinding machine. The sheet is fed to a leveling machine that flattens and
levels the coming sheets. The leveling machine also feeds the sheets to a machine centre where the sheets are cut and punched at the same time using a punch and die arrangement. The output strips are collected at the bottom of the punch. Steel rods are used to locate the resulting fins and also to collect them. The process is shown in figure 6.8 below demonstrating the input/output of each step in the process.

![Diagram showing the process of aluminum fins production](image)

**Figure 6-8: Aluminum fins production process.**

The process has only two inputs, which are aluminum and energy. The scrape rate of this process is zero. There is no scrap produced and all input material goes into the final product. The energy input for each step that is required to produce one functional unit (one AC) is specified in figure 6.8. The source of energy for all steps is electricity. The emission associated with electricity is related to the energy mix and energy generation fuel. Major emissions associated with production of 1 kWh electricity in Saudi Arabia, as is shown in table 6.5 below. Also, the table shows the emission associated with total energy consumed by the process which is 0.89 kWh per functional unit.

**Table 6-5: Sample emission associated with electricity usage in aluminum fins manufacturing**

<table>
<thead>
<tr>
<th>Emission</th>
<th>Emission kg per 1 kWh</th>
<th>Emission (kg) per functional unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emission</td>
<td>0.757</td>
<td>673.73</td>
</tr>
<tr>
<td>SO₂ emissions</td>
<td>1.235E-03</td>
<td>1.09915</td>
</tr>
<tr>
<td>The NOₓ emissions</td>
<td>0.463E-03</td>
<td>0.41207</td>
</tr>
</tbody>
</table>
As there is no complete dataset for emissions from generating electricity in Saudi Arabia, electricity generation data from the United States is used to model the LCI of this process using GaBi.

The start of the life cycle inventory of copper tube manufacturing begins with unrolling the copper tubes through a set of rollers which feed a rotating cutter that cuts the tubes to the required length. Then the tubes are fed to bending machine to form the ‘U’ shape of the pipe, another machine is used to form smaller pieces and a ‘C’ shape that will be used to connect two U tubes and form a continuous piping system for the evaporator and also for the condenser. The process is demonstrated in Figure 6.9.

![Diagram of copper tube manufacturing process](image)

**Figure 6-9: Manufacturing process of copper tubes, ‘U’ shapes and ‘C’ shapes.**

The life cycle inventory of the process is electrical energy and copper tubes as input, while the output is ‘U’ and ‘C’ shaped copper tubes. The emission associated with copper tube production is similar to the ones in aluminum fins production, as is shown in Table 6.6 below.

**Table 6-6: Sample emission associated with copper tube manufacturing**

<table>
<thead>
<tr>
<th>Emission</th>
<th>Emission kg per 1 kWh</th>
<th>Emission (kg) per functional unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emission</td>
<td>0.757</td>
<td>0.601</td>
</tr>
<tr>
<td>SO₂ emissions</td>
<td>1.235 E-03</td>
<td>0.982 E-03</td>
</tr>
<tr>
<td>The NOx emissions</td>
<td>0.463 E-03</td>
<td>0.368 E-03</td>
</tr>
</tbody>
</table>
The manufacturing phase is modeled using GaBi software. Note that electricity is the only source of any life cycle impact associated with this phase. Figure 6.10 shows the main processes in manufacturing phase and their input electricity. Detailed inventory can be found in GaBi’s professional database.

![Figure 6-10: Manufacturing phase model using GaBi software.](image)

6.3.1.3 Assembly phase

The assembly phase consists of the following steps:

1. Evaporator/condenser assembly and brazing.
2. Parts assembly to bottom plate.
3. Assembly of piping system using brazing.
4. Enclosure assembly.
5. R22 refrigerant charging.

The first three steps are different for new AC and remanufactured AC. The difference depends on how many of the parts are recovered in the remanufacturing process. The
second step is done manually with power tools which consume small power comparing to other manufacturing machines.

The copper tubes and aluminum fins are assembled manually to form the evaporator and condenser. As the process is done manually there is no associated LCI. The last step in the assembly process is brazing the ‘C’ shape copper tube to ‘U’ shape ones to form continuous piping in the evaporator/condenser. The LCI associated with the brazing process is demonstrated in table 6.7 below, the LCI is obtained from ELCID database provided by GaBi. Finally, assembly of the enclosure is done with the help of power tools. Their electrical power consumption is counted together with other power tools used in the assembly phase and model in one process as shown in figure 6.11.

**Table 6-7: Sample of life cycle inventory of brazing using liquefied petroleum gas (LPG)**

<table>
<thead>
<tr>
<th>Flow</th>
<th>Unit</th>
<th>Amount/1 liter</th>
<th>Amount/1 functional unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Outputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide, fossil</td>
<td>kg</td>
<td>1.72</td>
<td>0.344</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>kg</td>
<td>0.000443</td>
<td>8.86E-05</td>
</tr>
<tr>
<td>Dinitrogen monoxide</td>
<td>kg</td>
<td>0.000117</td>
<td>2.34E-05</td>
</tr>
<tr>
<td>Methane</td>
<td>kg</td>
<td>0.000026</td>
<td>5.2E-06</td>
</tr>
<tr>
<td>Nitrogen oxides</td>
<td>kg</td>
<td>0.0026</td>
<td>0.00052</td>
</tr>
<tr>
<td>Particulates, &gt; 2.5 um, &amp; &lt; 10 um</td>
<td>kg</td>
<td>0.0000781</td>
<td>1.56E-05</td>
</tr>
<tr>
<td>Volatile organic compounds (VOC)</td>
<td>kg</td>
<td>0.0000455</td>
<td>9.1E-06</td>
</tr>
<tr>
<td><strong>Inputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquefied petroleum gas, at refinery</td>
<td>Liter</td>
<td>1</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The LPG quantity required for brazing one new AC unit is calculated based on annual consumption and production of the industrial partner, 0.2 liter of LPG is needed to braze one unit. This is equivalent to 5 MJ (1 L= 25 MJ). Figure 6.11 illustrates GaBi model for the assembly phase. Electricity is needed to perform the assembly process
using power tools. It is calculated, based on the power rating of the tools, and is found to be 1.62 MJ. Detailed inventory can be found in GaBi’s professional database. The model also includes the effect of using R22, which is shown in the charging process as an output flow that will eventually go to air as emission.

Figure 6-11: Assembly phase model using GaBi software.

6.3.1.4 Use phase

The life cycle inventory of the unit function depends on the assumption and constraints of the actual patterns of uses. To maintain the quality and consistency of the analysis the following assumptions are stated:

1. Useful life is 5 years.
2. Average operating hours per day is 16 hours.
3. Average annual improvement in energy efficiency is 2% (based on historical data).
4. The power rating for the 18,000 BTU unit is 1.75 kW.

The total consumption of the electrical energy over the expected useful life is calculated as shown in Table 6.8.
Table 6-8: Energy consumption during use phase

<table>
<thead>
<tr>
<th>Year</th>
<th>Consumption (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 1</td>
<td>10,220.0</td>
</tr>
<tr>
<td>Year 2</td>
<td>10,015.6</td>
</tr>
<tr>
<td>Year 3</td>
<td>9,811.2</td>
</tr>
<tr>
<td>Year 4</td>
<td>9,606.8</td>
</tr>
<tr>
<td>Year 5</td>
<td>9,402.4</td>
</tr>
<tr>
<td>Total</td>
<td>49,056</td>
</tr>
</tbody>
</table>

The total energy consumed over the useful life is 49056 kWh (17660 MJ), this consumption is based on a 2% improvement in energy efficiency. The inventory analysis of the electrical energy is shown in table 6.9 below.

Table 6-9: Sample emission associated with the use phase of a functional unit

<table>
<thead>
<tr>
<th>Emission</th>
<th>Emission (kg) per functional unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2 emission</td>
<td>2623.16537</td>
</tr>
<tr>
<td>SO2 emissions</td>
<td>0.365</td>
</tr>
<tr>
<td>The NOx emissions</td>
<td>0.000114262</td>
</tr>
</tbody>
</table>

Use phase is modeled using GaBi as shown in figure 6.12, and its associated detailed inventory can be found in GaBi’s professional database.
6.3.2 Life cycle inventory of remanufactured AC

Currently there is no existing plant that produces remanufactured AC. The remanufacturing process designed in chapter five is used to analyse the lifecycle inventory of remanufactured AC.

6.3.2.1 Collection

Life cycle inventory of the collection phase consists of two major processes: transport and inspection. Since inspection is done visually no inventory is associated with this process. Transportation requires a diesel refinery. This process should be included in this phase’s inventory in addition to the transportation of an AC unit, a distance of 845.3 km. The collection phase is modeled using GaBi software, and the life cycle inventory is obtained based on the modeled phase which is shown in figure 6-13. A sample of the associated inventory is listed in Table 6.10 below. Detailed inventory can be found in GaBi’s professional database.

![Figure 6-13: Collection phase modeling using GaBi.](image-url)
Table 6-10: Sample LCI of the collection phase

<table>
<thead>
<tr>
<th>Input flow</th>
<th>Quantity (kg)</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cargo: End of life AC</td>
<td>1</td>
<td>Calculated</td>
</tr>
<tr>
<td>Diesel (Refinery products)</td>
<td>0.001635029</td>
<td>Calculated</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output flow</th>
<th>Quantity (kg)</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cargo: End of life AC</td>
<td>1</td>
<td>Calculated</td>
</tr>
<tr>
<td>Ammonia (Inorganic emissions to air)</td>
<td>3.20E-08</td>
<td>Literature</td>
</tr>
<tr>
<td>Benzene (Group NMVOC to air)</td>
<td>2.47E-09</td>
<td>Calculated</td>
</tr>
<tr>
<td>Carbon dioxide (Inorganic emissions to air)</td>
<td>0.004937933</td>
<td>Calculated</td>
</tr>
<tr>
<td>Carbon dioxide (biotic) (Inorganic emissions to air)</td>
<td>0.000259891</td>
<td>Calculated</td>
</tr>
<tr>
<td>Carbon monoxide (Inorganic emissions to air)</td>
<td>8.66E-06</td>
<td>Calculated</td>
</tr>
<tr>
<td>Dust (PM2.5) (Particles to air)</td>
<td>1.48E-07</td>
<td>Calculated</td>
</tr>
<tr>
<td>Methane (Organic emissions to air (group VOC))</td>
<td>3.55E-09</td>
<td>Calculated</td>
</tr>
<tr>
<td>Nitrogen dioxide (Inorganic emissions to air)</td>
<td>8.94E-07</td>
<td>Calculated</td>
</tr>
<tr>
<td>Nitrogen monoxide (Inorganic emissions to air)</td>
<td>1.19E-05</td>
<td>Calculated</td>
</tr>
<tr>
<td>Nitrous oxide (Inorganic emissions to air)</td>
<td>4.10E-08</td>
<td>Literature</td>
</tr>
<tr>
<td>NMVOC (unspecified) (Group NMVOC to air)</td>
<td>1.44E-07</td>
<td>Calculated</td>
</tr>
<tr>
<td>Sulphur dioxide (Inorganic emissions to air)</td>
<td>3.27E-08</td>
<td>Calculated</td>
</tr>
</tbody>
</table>

6.3.2.2 Disassembly

In the life cycle inventory the disassembly process is modeled by using GaBi software. Figure 6-14 shows the processes of this phase. The LCI of this phase is mainly due to electricity consumption in pipe cutting and undoing the screws. Output of the disassembly phase is the wanted parts that go through a further process of remanufacturing and the unwanted parts that go through material recycling. A sample of the LCI of disassembly phase is shown in Table 5.11 below. Detailed inventory can be found in GaBi’s professional database.
### Table 6-11: Sample LCI of disassembly phase

The LCI of the disassembly process
Based on electricity generated from natural gas

<table>
<thead>
<tr>
<th>Input flow</th>
<th>Quantity</th>
<th>Unit</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air (Renewable resources)</td>
<td>2.912637995</td>
<td>kg</td>
<td>(Calculated)</td>
</tr>
<tr>
<td>Antimony (Non renewable elements)</td>
<td>2.19E-11</td>
<td>kg</td>
<td>(No statement)</td>
</tr>
<tr>
<td>Natural gas (in MJ)</td>
<td>2.956265787</td>
<td>MJ</td>
<td>(Literature)</td>
</tr>
<tr>
<td>Barium sulphate (Non-renewable resources)</td>
<td>1.24E-16</td>
<td>kg</td>
<td>Literature</td>
</tr>
<tr>
<td>Basalt (Non-renewable resources)</td>
<td>3.60E-10</td>
<td>kg</td>
<td>Calculated</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Input Flow</th>
<th>Quantity</th>
<th>Unit</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity (Electric power)</td>
<td>3.6</td>
<td>MJ</td>
<td>Literature</td>
</tr>
<tr>
<td>High radioactive waste (Radioactive waste)</td>
<td>1.82E-09</td>
<td>kg</td>
<td>Literature</td>
</tr>
<tr>
<td>Low radioactive wastes (Radioactive waste)</td>
<td>3.05E-08</td>
<td>kg</td>
<td>Literature</td>
</tr>
<tr>
<td>Medium radioactive wastes (Radioactive waste)</td>
<td>1.55E-08</td>
<td>kg</td>
<td>Literature</td>
</tr>
<tr>
<td>Radioactive tailings (Radioactive waste)</td>
<td>1.42E-06</td>
<td>kg</td>
<td>(Calculated)</td>
</tr>
</tbody>
</table>

![Figure 6-14: Disassembly phase modeling using GaBi software.](image)

Figure 6-14: Disassembly phase modeling using GaBi software.
6.3.2.3 Cleaning

The cleaning process shown in figure 6.15 is used to identify the lifecycle inventory.

![Diagram of the cleaning process]

Figure 6.15: Processes of cleaning phase.

The design parameters and assumptions of this stage involve, as mentioned earlier in the previous chapter, the cleaning process. This is executed on each separate part of the remanufactured AC. The total life cycle inventory of this phase comes from its process’s individual LCI; they are:

1. LCI related to natural gas consumption in steam generation.
2. LCI related to electricity for compressed air.
3. LCI related to electricity for material handling conveyor.
4. LCI related to water desalination.
5. LCI related to waste water treatment.

As the steam generation process, electricity generation, and water desalination are assumed to use natural gas as a source of energy, the input and output of these processes are be the same. Only the quantity is different from one process to the other depending on how much is required to produce the reference quantity (i.e., 1 kg of desalinated water, 1 MJ of electricity, etc.).
Since the waste water treatment is conducted by the municipality, the input for this process is not traced back to their sources and processes that produce them, only direct input and output of the process are considered in the LCI. Detailed inventory can be found in GaBi’s professional database. The generated LCI is based on the model shown in Figure 6.16, the model is constructed using GaBi software.

**Figure 6-16: Cleaning phase modeling using GaBi software.**

### 6.3.2.4 Reassembly

The total life cycle inventory of this phase comes from its individual processes LCI, they are:

1. LCI related to LPG consumption in brazing process.
2. LCI related to electricity for parts inspection
3. LCI related to electricity for reassembly
4. LCI related to electricity for final inspection.

The generated LCI is based on GaBi model shown in Figure 6.17 the electricity used to perform part inspection, reassembly, and final product testing is generated from the same
source, so it is expected to generate the same type of inventory, the difference is only in the generated quantities of each process.

![Reassembly phase model using GaBi software.](image)

**Figure 6-17: Reassembly phase model using GaBi software.**

Table 6.12 shows sample LCI for LPG consumed in brazing process. Detailed inventory associated with each process in reassembly phase can be found in GaBi’s professional database.

**Table 6-12: Sample of LCI for LPG consumed in brazing process**

Error! Not a valid link.

6.3.2.5 **Use phase**

The life cycle inventory during the use phase is limited to the energy consumption. The only input in the use phase is energy obtained from electricity. Natural gas is the main source for generating electricity in Saudi Arabia, therefore the life cycle inventory of the use phase is built based on a process that generates electricity from natural gas. GaBi software is used to model the use phase as shown in figure 6.18 below. Detailed inventory can be found in GaBi’s professional database.
The LCI for the disposal phase is not considered in this study, since both the remanufactured AC and the new AC have equal opportunity to go through the same recovery option. This brings the LCI analysis to its end. The impact assessment can start at this stage. In the next chapter impact assessment is conducted using GaBi software which uses assessment methodologies commonly found in the literature.

6.4 Summary

In this chapter the life cycle inventory for both new and remanufactured AC is identified. The actual processes for manufacturing new AC are analyzed to identify the associated inventory. Lifecycle inventory of remanufactured AC is identified based on the remanufacturing process designed in chapter five. The identified inventory serves as input for the next stage in the comparison. Lifecycle impact assessment is conducted in the next chapter.
7 LIFE CYCLE IMPACT ASSESSMENT (LCIA) AND RESULTS

INTERPRETATION

7.1 Introduction

In this chapter, the life cycle impacts are assessed for new AC as well as the remanufactured AC. The assessment method should rely on authentic characterization models that relate each item in the life cycle inventory to the appropriate category or categories of life cycle impacts. This study depends on characterization models found in GaBi software. Section 7.2 describes the available assessment method in GaBi as well as impact categories considered in this research. Section 7.3 elaborates on GaBi software as a life cycle impact assessment tool.

The main role of this chapter is to answer research questions found in Chapter 1, which are related to the environmental impacts of the new AC compared to the remanufactured AC. Section 7.3 discusses the impacts of the new AC. Section 7.4 discusses the impacts of remanufactured AC. Next, section 7.5 assesses the difference between the two life cycles. Finally, the sensitivity analysis is conducted to test different scenarios and to assess their influence on the final results of environmental impacts.

7.2 Assessment methods

Many assessment methods can be found in the literature, in this section methods used by GaBi software are discussed, this includes:

1. CML 2001 method: It is a characterization method that was developed by Institute of Environmental Sciences, Leiden University, in The Netherlands. It contains more than 1,700 elements that are connected to their environmental impact(s).
The method keeps the analysis restricted to the first level of a cause-effect relationship, this is to reduce complexity as well as uncertainty.

2. **TRACI Method**: A life cycle impact assessment method developed by the United States Environmental Protection Agency. TRACI stands for Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts. TRACI uses a midpoint approach. The methodology assumes a simple cause-effect series to determine at which point each impact category is characterized.

3. **The ReCiPe Method**: It is a LCA methodology created by RIVM, CML, PRé Consultants, Radboud Universiteit Nijmegen and CE Delft in The Netherlands. The authors established their method based on CML 2001 and Ecoindicator 99 methodologies. It considers the midpoint effect as well as the end point in the series of impacts. For the midpoint approach; impact categories similar to ones in CML 2001 are considered. For endpoint categories, the endpoint categories are considered. These categories are: damage to resources; damage to human health; and damage to ecosystem.

4. **LCIA**: This method is based on a survey conducted by PE International (now Thinkstep, the company owns GaBi). The purpose of the survey is to determine the most important environmental impact to be considered in a LCIA. Five impacts are identified. LCIA is followed in this research.

### 7.3 GaBi software

Gabi Software is a tool to conduct life cycle impact assessments. It relies on the most comprehensive database in the world. Currently is owned by Thinkstep Company located in Germany. The software does LCIA as well as other services related to environmental
performance of products, processes, and systems. Thinkstep marketing describes the software in the following manner, “GaBi combines the world’s leading Life Cycle Assessment (LCA) modelling and reporting software, content databases with intuitive data collection and reporting tools.” (Thinkstep.com, 2016)

The usefulness of GaBi comes from its ability to access large databases and runs different scenarios easily and efficiently. GaBi LCIA methodology addresses the following five categories of environmental impacts:

1. Global Warming Potential (GWP): LCI gases that contribute to global warming are plentiful with CO, CO₂, N₂O as the major contributors. GWP is calculated by the summation of weights of gases that cause global multiplied by their CO₂ equivalency factor.

2. Ozone Depletion Potential (ODP): Ozone is mainly depleted due to emissions of chlorofluorocarbon (CFC) compounds and other halogenated hydrocarbons. ODP is calculated by summation of weights of emissions causing ozone depletion multiplied by their R11 equivalency factor.

3. Eutrophication Potential (EP): Eutrophication results from the over fertilization of water and soil that leads to increase the biomass in both. The main emissions that cause EP are phosphate, NH₃, and NOx. EP is calculated by the summation of weights of emissions that cause EP multiplied by their phosphate equivalency factor.

4. Photochemical Ozone Creation Potential (POCP): Indicates the potential of emission to degrade in the atmosphere to contribute to ozone creation. POCP is
calculated by summation of weights of emissions that cause POCP multiplied by their ethylene equivalency factor.

5. Acidification Potential (AP): Indicates the ability of emissions to create an acidic environment through creation of H⁺. Emissions like HCl, NOx, SO₂, NH₃ and HF are the main causes for AP. AP is calculated by summation of weights of emissions causing AP multiplied by their SO₂ equivalency factor.

7.4 Life cycle impact assessment (LCIA) of new AC

7.4.1 Material processing phase
The life cycle inventory studied in Chapter 5 is organized into five significant environmental impacts. Figure 6.1 illustrates the impacts of each process in this phase.

For the global warming potential (GWP) the most significant process that contributes to GWP is aluminum production, followed by copper tube production. These processes together contribute to more than 99% of the GWP. Sea shipping from the source of production to the manufacturing plant makes a minimal contribution. Included is the contribution from the production of fuel required to operate the ship. The values of individual contribution are shown in table 6.1.

When considering the ozone depletion potential (ODP) the most significant process that contributes to ozone depletion is copper production. Although its absolute value is low (1.73E-06), it is the highest among the rest of this phase processes. The next contributing process, aluminum production, is almost 50% of the copper production process. Sea shipping of the processed material has no contribution to ODP, this includes the fuel processing required to operate the shipping process. Figure 6.1 shows a bar chart of each process contribution to ODP.
In taking into account the eutrophication potential (EP) aluminum sheet production is the main contributor to this impact. It is more than double the next contributor, which is copper production. The transportation process has minimal contributions as shown in Figure 7.1

The acidification potential (AP) is another important factor to consider. AP impact is mainly related to aluminum sheet production as a major contributor and copper tube production as a minor contributor. Sea transportation has an almost negligible contribution to AP, it contributes to less than 1%. Figure 7.1 demonstrates the contribution to acidification impact of processes making up the material processing phase.

**Table 7-1: LCIA of materials processing phase—New AC**

<table>
<thead>
<tr>
<th>Processes</th>
<th>GWP</th>
<th>ODP</th>
<th>EP</th>
<th>POCP</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper production</td>
<td>2.23E+01</td>
<td>1.73E-06</td>
<td>5.66E-03</td>
<td>0.00607</td>
<td>9.11E-02</td>
</tr>
<tr>
<td>Aluminum production</td>
<td>7.10E+01</td>
<td>2.16E-08</td>
<td>0.0201</td>
<td>0.021</td>
<td>0.341</td>
</tr>
<tr>
<td>Heavy fuel for copper shipping</td>
<td>3.16E-03</td>
<td>8.72E-14</td>
<td>1.03E-06</td>
<td>3.02E-06</td>
<td>7.64E-06</td>
</tr>
<tr>
<td>Heavy fuel for AL shipping</td>
<td>1.41E-03</td>
<td>8.72E-14</td>
<td>4.71E-07</td>
<td>3.02E-06</td>
<td>1.66E-05</td>
</tr>
<tr>
<td>Ship transport for copper</td>
<td>9.90E-03</td>
<td>0</td>
<td>7.44E-05</td>
<td>4.12E-05</td>
<td>7.26E-04</td>
</tr>
<tr>
<td>Ship transport for AL</td>
<td>2.17E-02</td>
<td>0</td>
<td>3.42E-05</td>
<td>1.89E-05</td>
<td>3.33E-04</td>
</tr>
</tbody>
</table>
Figure 7-1: LCIA of material processing—New AC.
7.4.2 Manufacturing phase

Processes in the manufacturing phase are run by electricity, which comes from the same source. Electricity is the only source of energy used in the manufacturing processes. Hence, the impact of each process depends on the amount of consumed electricity.

When considering the GWP the manufacturing of aluminum fins makes the highest contribution to GWP as it contributes to more than 50% of the impact of manufacturing phase, Table 7.2 provide the details for the contributions of each process. Copper tube forming process is the next main contributor. Electricity consumed in the storage of raw materials has the lowest impact. Figure 7.2 illustrates the contributions of manufacturing phase processes along with their impacts contributions.

- Ozone Depletion Potential (ODP): Analysis are identical as in GWP.
- Eutrophication Potential (EP): Analysis are identical as in GWP.
- Photochemical Ozone Creation Potential (POCP): Analysis are identical as in GWP.
- Acidification Potential (AP): Analysis are identical as in GWP.

Table 7-2: LCIA of manufacturing phase—New AC

<table>
<thead>
<tr>
<th>Processes</th>
<th>GWP</th>
<th>ODP</th>
<th>EP</th>
<th>POCP</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage—Electricity</td>
<td>1.04E-02</td>
<td>3.87E-11</td>
<td>1.90E-06</td>
<td>9.58E-06</td>
<td>3.18E-04</td>
</tr>
<tr>
<td>Al Fins Manufacturing—Electricity</td>
<td>5.90E-01</td>
<td>2.19E-10</td>
<td>1.08E-04</td>
<td>1.10E-04</td>
<td>1.79E-03</td>
</tr>
<tr>
<td>Copper tubes man.—Electricity</td>
<td>5.17E-01</td>
<td>1.92E-10</td>
<td>9.44E-05</td>
<td>9.65E-05</td>
<td>1.57E-03</td>
</tr>
<tr>
<td>Total</td>
<td>1.12E+00</td>
<td>4.50E-10</td>
<td>2.04E-04</td>
<td>2.16E-04</td>
<td>3.68E-03</td>
</tr>
</tbody>
</table>
Figure 7-2: LCIA of manufacturing phase—New AC.
7.4.3 Assembly phase

In this phase the GWP is mainly due to R22 refrigerant charged to the system and 1 kg of R22 is charged per new AC unit, which contributes to the most of GWP in this phase, almost 99%. The rest of the processes contribute to 1% of global warming impact. See Table 7.3 for more details.

In this phase the ODP is important, with R22 playing a significant contribution. Since R22 is one of the gases identified as an ozone depletion factor. R22 charging is a significant process that creates the GWP of this phase. The contribution of the remaining processes is negligible. See Figure 7.3 for further details.

Brazing process that uses LPG as a source of energy, produces the most of EP. It is responsible for 78% of the EP, while assembly process using electricity generates the rest of EP. It is found that R22 charging has no effect on EP.

The most significant process that produces the most of POCP is the brazing process. It is responsible for 78% of the POCP, while the assembly process uses electricity that generates the rest of POCP. The R22 charging process has no link to POCP.

The AP is highly connected to electricity consumption. Electricity consumed in the assembly process is responsible for almost 60% of AP. While the brazing process contributes to the rest. Figure 7.3 shows the contribution of these processes to AP and table 7.3 gives detailed numbers of each contribution. As indicated in the table, the contribution of R22 charging is zero.
Table 7-3: LCIA of assembly phase

<table>
<thead>
<tr>
<th>Processes</th>
<th>GWP</th>
<th>ODP</th>
<th>EP</th>
<th>POCP</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly process—Electricity</td>
<td>2.98E-01</td>
<td>1.10E-10</td>
<td>5.45E-05</td>
<td>5.57E-05</td>
<td>9.06E-04</td>
</tr>
<tr>
<td>Brazing—LPG</td>
<td>4.37E-01</td>
<td>2.93E-12</td>
<td>1.14E-04</td>
<td>9.04E-05</td>
<td>6.34E-04</td>
</tr>
<tr>
<td>Charging R22</td>
<td>1.81E+03</td>
<td>5.00E-02</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Total</td>
<td>1.81E+03</td>
<td>5.00E-02</td>
<td>1.69E-04</td>
<td>1.46E-04</td>
<td>1.54E-03</td>
</tr>
</tbody>
</table>

7.4.4 Use phase

The only life cycle inventory identified in the use phase is electricity, hence all environmental impacts resulting from this phase are associated with electricity consumption.

The GWP in this phase has a very high absolute value of GWP compared to the GWP of the whole life cycle of a new AC. It contributes to almost 95% of GWP of the whole life cycle. See table 7.4 for actual values.

The ODP of the use phase has a minimal contribution to ODP, almost no contribution at all. While the EP associated with the use phase is the highest among all phases. In this phase the POCP has the same significance as the EP and AP. Figure 7.4 demonstrates the amount of use phase impacts.

Table 7-4: LCIA of use phase—New AC

<table>
<thead>
<tr>
<th>Process</th>
<th>GWP</th>
<th>ODP</th>
<th>EP</th>
<th>POCP</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use Phase—Electricity</td>
<td>3.31E+04</td>
<td>1.23E-05</td>
<td>6.05E+00</td>
<td>6.19E+00</td>
<td>1.01E+02</td>
</tr>
</tbody>
</table>
Figure 7-3: LCIA of assembly phase.
Figure 7-4: LCIA of use phase—New AC.
7.4.5 Whole lifecycle phases—New AC

The use phase is the most significant contributor to GWP by contributing 94%, followed by assembly phase, which contributes 4%. The rest is contributed by the remaining phases. The ODP of new AC life cycle is mainly due to charging of R22 refrigerant, which happens during the assembly phase. The contributions of other phases are negligible. The use phase is responsible for the most of EP. That is due to large amount of electricity consumed over its useful life. Material processing phase is the next significant phase that contributes to EP. The POCP occurs mainly in the use phase as 99% of POCP is generated during the use phase. AP contributions are identical to EP.

Figure 7.5 shows the contribution of every phase by the five selected environmental impacts. Detailed values are listed in table 7.5 below.

Table 7-5: LCI of all lifecycle phases of new AC

<table>
<thead>
<tr>
<th>Life cycle phases</th>
<th>GWP</th>
<th>ODP</th>
<th>EP</th>
<th>POCP</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials Processing</td>
<td>9.33E+01</td>
<td>1.75E-06</td>
<td>2.59E-02</td>
<td>0.027136</td>
<td>4.33E-01</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>1.20E+00</td>
<td>4.50E-10</td>
<td>0.000204</td>
<td>0.000216</td>
<td>0.003678</td>
</tr>
<tr>
<td>Assembly</td>
<td>1.80E+03</td>
<td>5.00E-02</td>
<td>1.69E-04</td>
<td>1.46E-04</td>
<td>1.54E-03</td>
</tr>
<tr>
<td>Use</td>
<td>3.30E+04</td>
<td>1.23E-05</td>
<td>6.05E+00</td>
<td>6.19E+00</td>
<td>1.01E+02</td>
</tr>
<tr>
<td>Total</td>
<td>3.49E+04</td>
<td>5.00E-02</td>
<td>6.08E+00</td>
<td>6.22E+00</td>
<td>1.01E+02</td>
</tr>
</tbody>
</table>
Figure 7-5: LCIA of all phases—New AC.
7.5 Life cycle impact assessment (LCIA) of remanufactured AC

7.5.1 Collection phase

In the collection phase the GWP of this phase comes from diesel consumption and its production at the refinery. Diesel’s production process is the main contributor to ODP in this phase, diesel consumption during transport does not contribute to OD. In the collection phase the truck transportation process is the most significant contributor to EP, as it contributes to 66% of the total EP. The production of diesel is the second contributor with 44%. Truck transportation process contributes negatively to POCP, it produces 0.00193 kg equivalent of ethylene. While diesel production produces 3.37E-04 kg. The net impact of this phase is negative. A significant contribution of AP comes from transportation as it contributes to 65%. The rest is associated to diesel production. Figure 7.6 shows the contribution of every process in this phase to the five selected environmental impacts. Detailed values are listed in table 7.6 below.

Table 7-6: LCIA of collection phase

<table>
<thead>
<tr>
<th>Processes</th>
<th>GWP</th>
<th>ODP</th>
<th>EP</th>
<th>POCP</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck transport</td>
<td>2.11E+00</td>
<td>0.00E+00</td>
<td>1.02E-03</td>
<td>-0.00193</td>
<td>3.88E-03</td>
</tr>
<tr>
<td>Diesel production</td>
<td>2.11E+00</td>
<td>2.04E-11</td>
<td>5.17E-04</td>
<td>3.37E-04</td>
<td>3.88E-03</td>
</tr>
<tr>
<td>Total</td>
<td>4.22E+00</td>
<td>2.04E-11</td>
<td>1.54E-03</td>
<td>-1.59E-03</td>
<td>7.76E-03</td>
</tr>
</tbody>
</table>
Figure 7-6: LCIA of collection phase.
7.5.2 Disassembly phase

The impacts generated due to disassembly phase come from electricity usage during the cutting process and disassembly using powered tools. Both processes use electricity that comes from the same source, consequently the generated impacts of these two processes are proportional to their consumed electricity. The life cycle inventory analysis shows that the pipe cutting process uses less electricity than the disassembly process. The impact associated with the pipe cutting process are expected to be less than impacts generated by disassembly process.

In this phase the disassembly process contributes to 85% of total GWP. The rest is contributed by cutting processes, table 7.7 provides the detailed contribution of each process. Figure 7.7 illustrates the contributions of the disassembly phase processes along with their impacts contributions. The same contributions apply to the following impacts:

- Ozone Depletion Potential (ODP).
- Photochemical Ozone Creation Potential (POCP).
- Acidification Potential (AP).

**Table 7-7: LCIA of disassembly phase**

<table>
<thead>
<tr>
<th>Processes</th>
<th>GWP</th>
<th>ODP</th>
<th>EP</th>
<th>POCP</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe cutting—Electricity</td>
<td>5.52E-02</td>
<td>2.50E-11</td>
<td>1.01E-05</td>
<td>1.03E-02</td>
<td>1.68E-04</td>
</tr>
<tr>
<td>Disassembly—Electricity</td>
<td>3.11E-01</td>
<td>1.23E-10</td>
<td>6.05E-05</td>
<td>6.90E-02</td>
<td>1.01E-03</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3.66E-01</strong></td>
<td><strong>1.48E-10</strong></td>
<td><strong>7.06E-05</strong></td>
<td><strong>7.93E-02</strong></td>
<td><strong>1.18E-03</strong></td>
</tr>
</tbody>
</table>
Figure 7-7: LCIA of disassembly phase.
7.5.3 Cleaning phase

In the cleaning phase the steam generating process is the most significant process that contributes to GWP (90%). It is followed by cleaning and drying using compressed air, electricity consumed in these two processes makes up 5% of the total GWP. The rest of processes in the cleaning phase contribute to 5% of the impact. Figure 7.8 shows the contribution of each process to GWP. Since the steam cleaning process contributes to 90% of GWP, alternative cleaning processes could have a lower impact.

Processes that use electricity contribute to the most of the ODP in this phase, Compressed air cleaning as well as the drying process and material handling process contribute to 96% of the ODP. The rest of the processes contribute to 5%. Waste water products are a concern with steam cleaning as it is the most significant process that produces EP at 85%. It is assumed that waste water is controlled by the remanufacturer, hence all generated waste water goes to municipal waste water treatment plant.

Steam generation and water desalination related to steam cleaning process are the most significant contributors to POCP and both contribute to almost 90% of the total POCP. Additionally, the steam generation process and electricity required by cleaning and drying produce up to 87% of AP. The rest of the impact comes from remaining processes.

Table 7-8: LCIA of cleaning phase

<table>
<thead>
<tr>
<th>Processes</th>
<th>GWP</th>
<th>ODP</th>
<th>EP</th>
<th>POCP</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed air—Electricity</td>
<td>6.70E-02</td>
<td>2.50E-11</td>
<td>1.24E-05</td>
<td>1.26E-05</td>
<td>2.05E-04</td>
</tr>
<tr>
<td>Material handling—Electricity</td>
<td>2.17E-02</td>
<td>8.05E-12</td>
<td>3.97E-06</td>
<td>4.05E-05</td>
<td>6.60E-05</td>
</tr>
<tr>
<td>Waste water</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>7.98E-04</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Water desalination</td>
<td>2.47E-02</td>
<td>9.50E-13</td>
<td>1.13E-05</td>
<td>4.05E-05</td>
<td>4.40E-05</td>
</tr>
<tr>
<td>Generating steam</td>
<td>1.06E+00</td>
<td>4.77E-13</td>
<td>1.05E-04</td>
<td>1.02E-04</td>
<td>5.50E-04</td>
</tr>
<tr>
<td>Total</td>
<td>1.17E+00</td>
<td>3.45E-11</td>
<td>9.31E-04</td>
<td>1.96E-04</td>
<td>8.65E-04</td>
</tr>
</tbody>
</table>

7.5.4 Reassembly phase
Reassembly processes that use electricity contribute to 99% of the total GWP. Brazing processes that uses LPG has a minimal effect, this is due to small consumption of LPG. There is a negligible effect on ODP in the reassembly phase. The ODP value is in the order of E-10, see table 7.9 for details. The brazing process has negligible effect on EP, POCP, and AP. Where there is an impact comes from the reassembly processes that uses electricity. Figure 7.9 demonstrates the contributions of the reassembly processes with respect to each impact.

Table 7-9: LCIA of reassembly phase

<table>
<thead>
<tr>
<th>Processes</th>
<th>GWP</th>
<th>ODP</th>
<th>EP</th>
<th>POCP</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reassembly---Electricity</td>
<td>3.31E-01</td>
<td>1.23E-10</td>
<td>6.05E-05</td>
<td>6.19E-05</td>
<td>1.01E-03</td>
</tr>
<tr>
<td>Part inspection---Electricity</td>
<td>1.09E-01</td>
<td>4.03E-11</td>
<td>1.99E-05</td>
<td>2.03E-05</td>
<td>3.30E-04</td>
</tr>
<tr>
<td>Final inspection---Electricity</td>
<td>1.06E-01</td>
<td>3.93E-12</td>
<td>1.94E-05</td>
<td>1.98E-05</td>
<td>3.22E-04</td>
</tr>
<tr>
<td>Brazing---LPG</td>
<td>8.70E-05</td>
<td>0.00E+00</td>
<td>2.20E-08</td>
<td>1.80E-08</td>
<td>1.27E-07</td>
</tr>
<tr>
<td>Total</td>
<td>5.46E-01</td>
<td>1.67E-10</td>
<td>9.98E-05</td>
<td>1.02E-04</td>
<td>1.66E-03</td>
</tr>
</tbody>
</table>
Figure 7-8: LCIA of cleaning phase.
Figure 7-9: LCIA of reassembly phase.
7.5.5 Use phase

The only life cycle inventory identified in the use phase is electricity, hence all environmental impacts result from this phase are associated to electricity consumption. The absolute value of GWP of use phase is very high compared to GWP of the whole life cycle of a remanufactured AC. It contributes to almost 99% of GWP of the whole life cycle. Table 7.10 shows the values of each impact. The use phase has minimal contribution to ODP. EP, POCP, and AP associated with the use phase is the highest among all phases. Figure 7.10 demonstrates the amount of use phase impacts.

Table 7-10: LCIA of use phase

<table>
<thead>
<tr>
<th>Process</th>
<th>GWP</th>
<th>ODP</th>
<th>EP</th>
<th>POCP</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use phase—Electricity</td>
<td>3.38E+04</td>
<td>1.26E-05</td>
<td>6.90E+00</td>
<td>6.32E+00</td>
<td>1.03E+02</td>
</tr>
</tbody>
</table>

7.5.6 All phases in remanufactured AC life cycle

The use phase is the dominant among all phases. It contributes to almost 99% of all impacts generated during the remanufactured AC, see figure 5.11. The collection phase is the second significant contributor to GWP, followed by reassembly. Figure 5.12 shows impacts of life cycle phases with the absence of use phase. ODP is minimal for all phases in the remanufactured AC. The total is in the order of E-5, compared to the order of E-2 in case of the new AC. This can be related to the fact that remanufactured AC uses recovered refrigerant, thus it is exempt from its impact. Refrigerant is the main cause of ODP. The use phase is the most significant contributor to EP. The collection phase is the second contributor. Least significant is the disassembly phase with respect to EP. Truck transportation using diesel in the collection phase produces a negative impact on POCP. This improves the performance of the remanufactured AC with respect to this
impact. This improvement is removed by the high impact that comes from use phase, the resultant impact is shown in table 7.11 as well as the detailed values of other impacts.

The use phase generates the most of AP, the least significant phase is cleaning, the cleaning process generate waste water that doesn’t have pollutant other than the dirt that comes from mostly sand and dust, hence its impact is negligible. Further more the treatment of waste water is not considered in the LCI of the cleaning phase, see section 5.3.2.

Table 7-11: LCIA All phases—Remanufactured AC

<table>
<thead>
<tr>
<th>Life cycle phases</th>
<th>GWP</th>
<th>ODP</th>
<th>EP</th>
<th>POCP</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collection</td>
<td>4.22E+00</td>
<td>2.04E-11</td>
<td>1.54E-03</td>
<td>-0.001593</td>
<td>7.76E-03</td>
</tr>
<tr>
<td>Disassembly</td>
<td>3.66E-01</td>
<td>1.48E-10</td>
<td>0.0000706</td>
<td>0.0690103</td>
<td>0.001178</td>
</tr>
<tr>
<td>Cleaning</td>
<td>1.17E+00</td>
<td>3.45E-11</td>
<td>9.31E-04</td>
<td>1.96E-04</td>
<td>8.65E-04</td>
</tr>
<tr>
<td>Reassembly</td>
<td>5.46E-01</td>
<td>1.67E-10</td>
<td>9.98E-05</td>
<td>1.02E-04</td>
<td>1.66E-03</td>
</tr>
<tr>
<td>Use</td>
<td>3.38E+04</td>
<td>1.26E-05</td>
<td>6.90E+00</td>
<td>6.32E+00</td>
<td>1.03E+02</td>
</tr>
<tr>
<td>Total</td>
<td>3.38E+04</td>
<td>1.26E-05</td>
<td>6.90E+00</td>
<td>6.39E+00</td>
<td>1.03E+02</td>
</tr>
</tbody>
</table>
Figure 7-10: LCIA of use phase—New AC.
Figure 7-11: LCIA All phases—Remanufactured AC.
Figure 7-12: LCIA All phases except use phase—Remanufactured AC.
7.6 Life cycle impact assessment (LCIA) of remanufactured AC compared to new AC

7.6.1 Direct comparison

The comparison between new and remanufactured unit depends on multi criteria; these criteria have different importance as well as different measuring unit. Hence, direct comparison is not possible. Romualdas Ginevičius (2008) suggested the use of so-called SAW (Simple Additive Weighting) method expressed as the following:

\[ S_i = \sum_{i=1}^{m} W_i \tilde{r}_{ij} \]

Where:

\( S_j \) is the value obtained in multicriteria evaluation of the \( j \)-th alternative;

\( W_i \) is the \( i \)-th criterion weight;

\( \tilde{r} \) is normalized value of the \( i \)-th criterion for the \( j \)-th alternative.

As can be seen from the above formula, normalized values are needed to determine the quantity of multicriteria evaluation. The sequence of normalization operations depends on the methods of multicriteria evaluation used. Calculating by SAW, normalization is based on the formula given by (Ginevičius, Podvezko 2004b; Ginevičius, Butkevičius, Podvezko 2005):

\[ \tilde{r} = \frac{r_{ij}}{\sum_{j=1}^{n} r_{ij}} \]

Where:

\( \tilde{r} \) is average normalized value.

\( r_{ij} \) is the \( i \)-th value of the \( j \)-th alternative.
The Wi for each criterion is obtained using experts opinion; a team of six experts are consulted to give appropriate weight for each criterion of the five criteria used in the evaluation of both options. The average weight is calculated and shown in Table 7.12. The results obtained from LCIA for both options are summarized in Table 7.12. The total impact of new AC is calculated as per the equation below

\[ S_i = \sum_{i=1}^{m} W_i \tilde{r}_j \]

\[ S_i = 0.647 \]

The total impacts of the remanufactured AC is calculated using the same formula and is found to be equal to 0.352. Comparison of the two normalized values shows that remanufacturing option has less total impact than new AC. Yet, careful look on the details is needed.

The GWP of the remanufactured AC is less than the equivalent new AC. The assumed 2% improvement in energy consumption of the new AC does not outweigh the energy required to produce the raw material for the new AC. The main contributor to the GWP of the new AC comes from R22 charging during the assembly phase. If charged R22 is recovered at the end of new AC life cycle this would reduce its GWP. It is worth mentioning that the improvement is limited, it is only 3%. This indicates that the remanufacturing option does not have an advantage from the GWP point of view. A low percentage of improvement doesn’t justify risks associated with the remanufacturing option.

The remanufactured option, however, is superior in ODP. This is due to the fact of using recovered R22. In this case ODP caused by charging the refrigerant does not add any impact. However, the new AC assumes the full impact. As indicated in table 6.12 the
improvement is 100% with respect to ODP. This makes remanufacturing an attractive option. The new AC option performs better with respect to EP, POCP, and AP. The main reason behind this is the impact generated during use phase. The new AC is 2% better than the remanufactured AC in terms of energy consumption during the use phase. This reveals a critical juncture where the decision regarding either AC option is highly sensitive to this assumption. If it is assumed that improvement is not achieved, the remanufactured AC becomes a better option with respect to these three impacts.

Table 7-12: LCIA comparison between new AC and remanufactured AC

<table>
<thead>
<tr>
<th>Weight (Wi)</th>
<th>GWP</th>
<th>ODP</th>
<th>EP</th>
<th>POCP</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCIA All phases—New AC</td>
<td>0.3</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>LCIA All Phases—Remanufactured AC</td>
<td>33806.3</td>
<td>1.26E-05</td>
<td>6.90264</td>
<td>6.38772</td>
<td>103.012</td>
</tr>
<tr>
<td>Normalized value -New AC</td>
<td>0.50792</td>
<td>0.99975</td>
<td>0.46816</td>
<td>0.49325</td>
<td>0.49615</td>
</tr>
<tr>
<td>Normalized value -Remanufactured AC</td>
<td>0.49208</td>
<td>0.00025</td>
<td>0.53184</td>
<td>0.50675</td>
<td>0.50385</td>
</tr>
<tr>
<td>Weight (Wi)* normalized value -new AC</td>
<td>0.15238</td>
<td>0.29992</td>
<td>0.04682</td>
<td>0.04932</td>
<td>0.09923</td>
</tr>
<tr>
<td>Weight (Wi)* normalized value -Remanufactured AC</td>
<td>0.14762</td>
<td>7.6E-05</td>
<td>0.05318</td>
<td>0.05068</td>
<td>0.10077</td>
</tr>
</tbody>
</table>

7.6.2 Comparison of Alternatives of Unequal Lives using Least Common Multiple

Direct comparison is not valid unless the two option has the same life span. The new AC can go in a reuse phase estimated to be 2 years before it reaches its end of life; while remanufactured unit is assumed to sustain shorter life during the reuse phase, half of the new unit is assumed here. Figure 7.13 below shows the life span of the two options.
The total span life of a new AC is 7 years, while the total span life for remanufactured is 11 years. The least common multiple between the two alternatives is 77 years.

The total impact of alternative is calculated as follows:

\[
\text{New AC impact} = 11 \times (\text{impact of 5 years as new} + \text{impact of 2 years as reuse})
\]

\[
= 11 \times (0.647 + 0.196) = 9.273
\]

\[
\text{Remanufactured AC impact} = 7 \times (\text{impact of 5 years as new} + \text{impact of 5 years as Rem} + \text{impact of 1 year as reuse})
\]

\[
= 7 \times (0.647 + 0.352 + 0.101) = 7.7
\]

The above calculations show that the total impact of remanufactured unit is less than the total impact of new AC during their common life span. It can be concluded that the environmental performance of remanufacturing alternative is better than new AC.

In the next section Gabi software models for both options are employed to assess different scenarios and assumptions. These scenarios help in clarifying the obtained results and to assess how much of the decision is sensitive to the values of these scenarios and assumptions.

7.7 Sensitivity analysis

In this section the following scenarios are tested and obtained results are evaluated.

7.7.1 Scenario 1: Useful life increased to 10 years (double the assumed life)
An increase in useful life will affect the use phase impacts. Table 7.13 shows 10 years of consumption for a new AC, the total consumption is 93,321 kWh. For the remanufactured AC the total consumption over 10 years is annual consumption times 10 years, which is 10,220 x 10 = 102,200 kWh. The GaBi model is run for both cases and the following results are obtained. Table 7.14 illustrates the final results.

Table 7-13: Ten years of electricity consumption—New AC

<table>
<thead>
<tr>
<th>Year</th>
<th>Consumption (kWh)</th>
<th>Year</th>
<th>Consumption (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 1</td>
<td>10,220</td>
<td>Year 6</td>
<td>9,214</td>
</tr>
<tr>
<td>Year 2</td>
<td>10,016</td>
<td>Year 7</td>
<td>9,030</td>
</tr>
<tr>
<td>Year 3</td>
<td>9,811</td>
<td>Year 8</td>
<td>8,849</td>
</tr>
<tr>
<td>Year 4</td>
<td>9,607</td>
<td>Year 9</td>
<td>8,672</td>
</tr>
<tr>
<td>Year 5</td>
<td>9,402</td>
<td>Year 10</td>
<td>8,499</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>49,056</strong></td>
<td><strong>Total</strong></td>
<td><strong>44,265</strong></td>
</tr>
</tbody>
</table>

Over 10 years of useful life the GWP impact generated from the use phase outweighs any gain due to remanufacturing. Only ODP remains with no change, other impacts get worse if remanufactured option is adopted.

Table 7-14: Scenario 1: Ten years of useful life

<table>
<thead>
<tr>
<th>Weight (Wi)</th>
<th>GWP</th>
<th>ODP</th>
<th>EP</th>
<th>POCP</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCIA All phases—</td>
<td>0.3</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>New AC</td>
<td>63694.5</td>
<td>0.05002</td>
<td>11.326</td>
<td>11.5272</td>
<td>188.438</td>
</tr>
<tr>
<td>LCIA All Phases—</td>
<td>0.3</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Remanufactured AC</td>
<td>67706.31</td>
<td>2.51E-05</td>
<td>12.4029</td>
<td>12.66</td>
<td>206.012</td>
</tr>
<tr>
<td>Normalized value -</td>
<td>0.4847344</td>
<td>0.99949</td>
<td>0.47730</td>
<td>0.47658</td>
<td>0.47772</td>
</tr>
<tr>
<td>New AC</td>
<td>0.515265</td>
<td>0.00050</td>
<td>0.522691</td>
<td>0.52341</td>
<td>0.52227</td>
</tr>
<tr>
<td>Normalized value -</td>
<td>0.145420</td>
<td>0.29984</td>
<td>0.047730</td>
<td>0.047658</td>
<td>0.09554</td>
</tr>
<tr>
<td>Remanufactured Ac</td>
<td>0.154579</td>
<td>0.00015</td>
<td>0.052269</td>
<td>0.052341</td>
<td>0.10445</td>
</tr>
</tbody>
</table>
The total normalized impact of ten year of use for new AC is equal to 0.6362, while the impact for the remanufactured unit is 0.3638, it’s obvious the expected efficiency improvement for new units doesn’t outweigh the benefits of remanufacturing.

### 7.7.2 Scenario 2: Energy efficiency increased to 10% (5 times the assumed efficiency)

The annual 10% improvement in energy consumption over the AC’s useful life of five years is calculated in Table 7.15 below. The new total consumption is 41,852 kWh.

<table>
<thead>
<tr>
<th>Year</th>
<th>Consumption (kWh)</th>
<th>Year</th>
<th>Consumption (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 1</td>
<td>10,220</td>
<td>Year 4</td>
<td>7,450</td>
</tr>
<tr>
<td>Year 2</td>
<td>9,198</td>
<td>Year 5</td>
<td>6,705</td>
</tr>
<tr>
<td>Year 3</td>
<td>8,278</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>41852 kWh</td>
</tr>
</tbody>
</table>

The GaBi model is run using new energy consumption. The obtained results are shown in Table 7.16 below.

It can be concluded from the results that more energy improvement makes the remanufacturing option unjustifiable. The exception is ODP, which remains unchanged. All other impacts are getting worse from remanufacturing option point of view. The overall impact of new AC is 0.5 and the overall impact of remanufactured one is 0.49. It can be concluded from the results that a 10% efficiency improvement is the breakeven point, and remanufacturing is not an appealing option after 10% improvement.
By comparing 10% energy improvement with the results of 2%, it can be seen that the difference is large enough such that decision can be taken not to remanufacture, if more than 10% efficiency improvement is achieved.

**Table 7-16: LCIA based on 10% energy efficiency improvement**

<table>
<thead>
<tr>
<th></th>
<th>GWP</th>
<th>ODP</th>
<th>EP</th>
<th>POCP</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCIA All phases—</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New AC</td>
<td>2.96E+04</td>
<td>5.00E-02</td>
<td>5.10E+00</td>
<td>5.21E+00</td>
<td>8.47E+01</td>
</tr>
<tr>
<td>LCIA All phases—</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remanufactured AC</td>
<td>3.38E+04</td>
<td>1.26E-05</td>
<td>6.90E+00</td>
<td>6.39E+00</td>
<td>1.03E+02</td>
</tr>
<tr>
<td>Normalized value—</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New AC</td>
<td>0.4669</td>
<td>0.9997</td>
<td>0.4250</td>
<td>0.4491</td>
<td>0.4513</td>
</tr>
<tr>
<td>Normalized value—</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remanufactured AC</td>
<td>0.5331</td>
<td>0.0003</td>
<td>0.5750</td>
<td>0.5509</td>
<td>0.5487</td>
</tr>
<tr>
<td>Weight (Wi)*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normalized value—</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>new AC</td>
<td>0.1401</td>
<td>0.1000</td>
<td>0.0850</td>
<td>0.0449</td>
<td>0.1354</td>
</tr>
<tr>
<td>Weight (Wi)*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normalized value—</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remanufactured AC</td>
<td>0.1599</td>
<td>0.0000</td>
<td>0.1150</td>
<td>0.0551</td>
<td>0.1646</td>
</tr>
</tbody>
</table>

**7.7.3 Scenario 3: R22 recovery increased to 50%, 90% (assumed current recovery is 0%)**

Ozone depletion is mainly due to unrecovered R22, this scenario’s purpose is to investigate the effect of R22 recovery on ODP. The first 50% of the new ACs are assumed to recover their refrigerant. Second, 90% of the new AC are assumed to recover their refrigerant at their EOL. These assumptions are fed into GaBi model that represent the assembly phase where the effect of R22 is considered. The model is run and the results in all cases have been recorded in Table 7.17.

Based on the results below the ODP of the new AC does not improve much as long as there is unrecovered R22. At 50% recovery, the improvement is null, due to the unrecovered 50%. The situation is almost the same at 90% recovery where the
unrecovered 10% gives remanufacturing option superiority over the new AC with respect to ODP. The situation does not improve unless 100% of R22 charged in the new AC is recovered by AC’s EOL. However, 100% recovery cannot be guaranteed due to the fact that manufacturers have no control over their produced ACs once these are delivered to the end user. To guarantee 100% recovery, a change in the current business model would have to elicit benefits such as a change to a product-service business model instead of the current one which assumes the full ownership of the product by the end user.

**Table 7-17: Scenario 3: 50%, 90%, and 100% R22 recovery at new AC’s end of life**

<table>
<thead>
<tr>
<th>Recovery Level</th>
<th>LCIA All Phases—New AC</th>
<th>LCIA All Phases—Remanufactured AC</th>
<th>Overall impact New AC</th>
<th>Overall impact Reman.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>50% recovery</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GWP</td>
<td>ODP</td>
<td>EP</td>
<td>POCP</td>
<td>AP</td>
</tr>
<tr>
<td>3.40E+04</td>
<td>2.50E-02</td>
<td>6.08E+00</td>
<td>6.22E+00</td>
<td>1.01E+02</td>
</tr>
<tr>
<td>3.38E+04</td>
<td>1.26E-05</td>
<td>6.90E+00</td>
<td>6.39E+00</td>
<td>1.03E+02</td>
</tr>
<tr>
<td>Overall impact New AC</td>
<td>0.64</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall impact Reman.</td>
<td></td>
<td></td>
<td></td>
<td>0.36</td>
</tr>
<tr>
<td><strong>90% recovery</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GWP</td>
<td>ODP</td>
<td>EP</td>
<td>POCP</td>
<td>AP</td>
</tr>
<tr>
<td>3.33E+04</td>
<td>5.01E-03</td>
<td>6.08E+00</td>
<td>6.22E+00</td>
<td>1.01E+02</td>
</tr>
<tr>
<td>3.38E+04</td>
<td>1.26E-05</td>
<td>6.90E+00</td>
<td>6.39E+00</td>
<td>1.03E+02</td>
</tr>
<tr>
<td>Overall impact New AC</td>
<td>0.62</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall impact Reman.</td>
<td></td>
<td></td>
<td></td>
<td>0.38</td>
</tr>
<tr>
<td><strong>100% recovery</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GWP</td>
<td>ODP</td>
<td>EP</td>
<td>POCP</td>
<td>AP</td>
</tr>
<tr>
<td>3.31E+04</td>
<td>1.41E-05</td>
<td>6.08E+00</td>
<td>6.22E+00</td>
<td>1.01E+02</td>
</tr>
<tr>
<td>3.38E+04</td>
<td>1.26E-05</td>
<td>6.90E+00</td>
<td>6.39E+00</td>
<td>1.03E+02</td>
</tr>
<tr>
<td>Overall impact New AC</td>
<td>0.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall impact Reman.</td>
<td>0.50</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
8 DISCUSSION AND CONCLUSIONS

8.1 Discussion

8.1.1 Remanufacturing

Is remanufacturing always an environmental rewarding recovery option? To answer this question this research work was undertaken. Remanufacturing is always marketed as the most environmental friendly recovery option. This claim is supported by the fact that stored value in parts and components are recovered. Attention should be paid to, however, the cost (environmental cost) of this recovery process. The case study of AC remanufacturing was utilized as an example to test if it would be a worthwhile exercise. The case study, regardless of the results, was not intended to be unquestioned evidence for the environmental usefulness of remanufacturing. The purpose was to investigate if remanufacturing of AC is environmentally rewarding or not. The AC example was carefully chosen as it was intended to represent a family of products which are characterized by intensive energy consumption during their use phase of their life cycle. This type of product usually goes through continuous improvement in its functional performance and this makes a newer model more efficient than older ones. It is case specific to decide whether the improved efficiency can outweigh the benefits of remanufacturing old ones or not.

8.1.2 Life cycle approach

This research provided a successful and comprehensive approach to answer the above mentioned query. The life cycle approach is found to be accurate and efficient in dealing with this research query. This research conducted a life cycle environmental impact assessment of both a new and a remanufactured AC. ISO 14044 was used to guide the
assessment process. It was found useful and helpful towards the achievement of the research objectives. Based on ISO 14044 guidelines the following objectives were successfully achieved:

- **Scope and goal of assessment**: Defining the goal of the study helped in defining the scope. For example, since the goal was to conduct a comparison between the new AC and a remanufactured one, it was found that the scope does not need to consider identical life cycle phases. This eliminated redundant work and reduced the complexity inherent in conducting LCIA.

- **LCI** was identified for phases that fall within the scope of the study. Attention was paid to quality of collected data. It was found that the assessment output depends on the quality of collected data. Data were collected carefully from the plant of the industrial partner. Experts’ judgement was sought to estimate unmeasurable data. The GaBi database was used to model many processes found in AC life cycle.

- **Environmental impact assessment** of both the new and remanufactured AC was determined using GaBi software. It provided authentic and accurate characterization approaches and models that link identified inventory to their related impact(s). Without the use of GaBi the characterization step would be time consuming, subjected to many shortcomings and would be less accurate.

- **Results** were obtained using GaBi and interpreted into a straightforward result. The purpose of this interpretation was to identify the most significant phase and/or process in the AC life cycle that contributes to a specify impact.
• GaBi’s LCIA characterization approach was selected in this research. The approach considered five environmental impacts to evaluate the performance of a studied product.

8.1.3 Research significance

The significance of this research is two-fold. First, it is a novel addition to the research community. It is a carefully documented and analyzed example that offers robust evidence that remanufacturing is not unquestionable recovery option. The results show that in some cases there is a breakeven point, where new and remanufactured unit perform equally from environmental point of view. Second, the developed life cycle models for new and remanufactured AC can be utilized to test and verify scenarios and assumptions according to decision maker preferences. With the aid of GaBi, the task can be performed by a non-expert. Useful information can be obtained and used to make informed decision.

8.2 Conclusions

The following conclusions can be drawn based on the conducted research:

• Although remanufacturing could be environmentally the most preferred recovery option, there are examples where this claim is not straight forward. AC remanufacturing is one of these examples. AC remanufacturing is found not to be an environmentally attractive recovery option in all cases, especially when it is compared with energy efficient new models of AC; sensitivity analyses shows that 10% improvement in energy efficiency of new model is a breakeven point; after this point remanufacturing is not justifiable.
• The life cycle approach is found capable in providing the accurate means to decide on the environmental performance of a product. In the example of AC, remanufacturing is very appealing when the comparison is based on saved material and parts during the manufacturing phase. When the assessment is extended to include a complete life cycle, the analysis shows that it is case sensitive, no generalized decision can be drawn.

• The environmental impact suggested by GaBi was found to be useful and comprehensive when evaluating the environmental performance of the studied product. It provides consistent and accurate results.

• GaBi was found efficient and accurate tool to conduct the LCIA. With GaBi, researchers have access to the world largest database of LCI. These analysts can have complete confidence in obtained results due to the fact that different characterization approaches and their results can be compared and evaluated for correctness.

• Without the help of GaBi, characterization would be a tedious and time consuming process. This study had the opportunity to utilize and benefit from a large number of characterization models built in the software.

• Sensitivity analysis gave insight into the environmental performance of the remanufacturing initiative. Testing different scenarios helped in both clarifying and defining breakeven points.

• The developed life cycle model is found to be efficient in testing different scenarios. The developed model in this research is straightforward enough for a
non-expert to run it and to obtain useful information enabling them in making informed decisions.

- The conducted sensitivity analyses showed that 10% energy efficiency improvement is the minimum improvement needed to make a new AC competitive compared to a remanufactured one.

- ODP is the main reason behind AC remanufacturing. R22 is fully recovered in the remanufacturing option.

- To reduce ODP in new ACs many options can be explored. As suggested by the sensitivity analysis 100% recovery of R22 is required. Another option is to switch to another refrigerant with no ODP.

- A new business model, based on product service system, could improve the environmental performance of the new AC unit. A product service system helps manufacturers maintain control over their product through the entire life cycle.

8.3 Assumptions and limitations

1. It should be noted that the obtained results in this research are case dependent. Results are tied to the industrial partner where the data was collected. Other AC manufacturers can benefit from this study, yet they need to be careful in applying its findings in their particular manufacturing plant, region, and product contexts.

2. Due to unavaibility of LCI for generated electricity in Saudi Arabia—the studied region, assumptions in the study were by using data obtained from the LCI related to the electricity mix in the US. Since this assumption was applied in analyzing both options, its effect will be minimal on the final results i.e., the option that
behaves better under a specific electricity mix will perform the same under another electricity mix.

3. There is inherent uncertainty in any LCIA. This same applies to the LCIA conducted in this research. This uncertainty is due to reasons, the most obvious one is the uncertainty in the data utilized in the LCI.

4. Since there is no existing remanufacturing plant, some processes were assumed and carefully documented. Obtained results are based on these assumptions and users are encouraged to refer to these assumptions found in Chapter 5 of this thesis.

5. The obtained results are based on GaBi’s characterization models and approaches. Different software might give different results. This should not affect the results’ credibility, as GaBi is the most accepted LCIA software worldwide.

8.4 Future work

In terms of future work, the following extension of the research can be done:

- Once a remanufacturing plant exists, data can be verified and an actual process can be modeled.
- Extending the research to assess different products that have the same characteristics as AC to verify the results and conclusions of this study.
- Constructing databases for processes related to the studied region, KSA.
- Include more criteria, other than environmental, to evaluate AC remanufacturing initiative. Technical and economical criteria might be useful to reach accurate decision about the overall performance of the initiative.
REFERENCES


Ziout A. Innovative Design for Active Disassembly and Sustainable Product Recovery, Electronic Theses and Dissertations, University of Windsor, 2013


APPENDIX:

10.1 Assemblies of Zamil Model 2007 Air conditioner (product of the study)
Aiman Ziout is a dedicated researcher in sustainable product and process design. He obtained his Bachelor and master degree from University of Jordan in Industrial Engineering. He accumulated professional experience in production management, mainly in steel industry. He obtained his PhD from University of Windsor-Canada. His main focus is sustainable production and sustainable product design. Currently he searches application of SMA in sustainable product design.