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Environmental Inventory Analysis for Remanufacturing Initiative: Case Study of Air Conditioner Remanufacturing

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Abstract: Remanufacturing is considered as the most preferable recovery option. The objective of this paper was to identify the environmental inventory of a remanufacturing initiative. A window-mount air conditioner (AC) was selected as a case study to verify the environmental benefits of remanufacturing a product characterized by high energy consumption during its life cycle phases. A life cycle approach was followed. The research aims to provide a reference case in the remanufacturing of products characterized by energy intensive use, of which an AC is one of them. The assessment was conducted with the guidance of the ISO 14044-2006 life cycle assessment (LCA). The significance of this study lies in the fact that it provides an authentic example wherein the environmental inventory of the remanufacturing process is identified and documented. It can be used in further studies to compare the environmental burden of remanufacturing processes to the process of manufacturing a new AC. The developed life cycle analysis can be utilized to help AC manufacturers make decisions about the overall environmental performance of their products if it goes through the remanufacturing cycle.

Keywords: life cycle assessment; environmental inventory; remanufacturing; sustainability; air conditioner

Citation: Ziout, A.; Alkahtani, M.; Elgawad, A.E.E.A.; Salah, B. Environmental Inventory Analysis for Remanufacturing Initiative: Case Study of Air Conditioner Remanufacturing. *Appl. Sci.* **2022**, *12*, 6251. https://doi.org/10.3390/app12126251

Academic Editor: Radu Godina

Received: 20 February 2022
Accepted: 17 June 2022
Published: 20 June 2022

1. Introduction

Air conditioner (AC) remanufacturing, like any other remanufacturing business, is motivated by saving resources, reducing environmental impacts, and generating financial profit. This study investigated one aspect of the remanufacturing process, which is the environmental inventory of the processes involved in the remanufacturing practice. The study considered remanufacturing ACs as an example of products characterized by high energy consumption during their use phase.

Resource consumption and environmental impacts occur during all phases of a product's life cycle. This study followed a life cycle approach to perform an investigation that analyzed the resource saving and environmental impacts throughout all phases in a product's life cycle. The analysis was conducted on an AC that operates in a hot region (Saudi Arabia) that also has a long summer of temperatures that can 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 natural gas and crude oil. The environmental impact associated with electricity generation can be linked directly to the use phase of the AC.

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 [1]. Technologies that facilitate these improvements are not predictable. However, there is 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, there are many aspects need to be investigated one of them, the subject of this paper, is the environmental inventory of remanufactured AC.

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, this paper identifies life cycle phases of a remanufactured AC, also it identifies the environmental inventory of the significant life cycle phases remanufactured

In summary, the objective of this study is to evaluate the life cycle inventory of air conditioner remanufacturing, this objective is essential to evaluate the environmental performance of this initiative. This study also aimed to identify the life cycle phases in AC remanufacturing as well as quantifying the environmental inventory of each phase.

2. Literature Review

Product recovery aims to divert end-of-life (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.

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 below.

Holmberg and Argerich [2] studied and addressed 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 steel. The life cycle assessment approach is followed to compare the environmental benefits of the remanufactured sub-frame with the new one.

The environmental significance of remanufacturing telecommunication networks equipment was studied by Goldey et al. [3]. Two types of equipment were used to conduct the study. The LCA approach was used to analyze the impacts of the 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 remanufacturing sustainability of alternators was studied by Schau et al. [4]. They conducted economic, societal, and environmental analyses. The life cycle assessment approach was used to analyze the environmental impacts of three types of alternators.

The remanufacturing of a diesel engine, in the Chinese truck industry, was the focus of a study by Shi et al. [5]. A life cycle assessment for a new diesel engine and its remanufactured equivalent with an upgrade to liquefied natural gas (LNG) was the subject of the study and showed that the remanufactured LNG engine had less environmental impact than a new equivalent diesel engine.

Liu et al. [6] implemented the cradle-to-gate life cycle assessment approach in assessing the remanufacturing of a diesel engine in the automotive industry. Six environmental categories were used to conduct the comparison.

Although the literature is rich in research that covers many aspects of remanufacturing, AC remanufacturing has not been fully addressed. The author is not aware of any industrial example of the full remanufacturing of an AC. In the literature, there is research that states that it deals with a 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 the remanufacturing of the compressor, and not the whole AC.

Yanagitani and Kawahara [7] used the life cycle assessment approach to compare the environmental performance of two different refrigerators that go into residential ACs. In this study, the authors compared the AC model HCFC22 (R22) to the AC model HFC410A. The study found that the HFCR410 had less ozone depletion potential along with a slight reduction in contributions to global warming potential

Zhang et al. [8] discussed the limitations of the LCA method; furthermore, they proposed the integration of remanufacturing and emerging technologies in the industry. Qiao and Su [9] found that it was not always a great strategy to increase government subsidies in order to decrease the environment pollution through remanufacturing or recycling. Before increasing government subsidies, policy makers need to learn more about the competitive markets and environmental impact per unit product. Zhang and Chen [10] analyzed the interaction between cleaner remanufacturing production and financing portfolio strategy, and a dyadic closed-loop supply chain model was constructed.

Remanufacturing cannot always be assumed as the best environmental recovery option, and scenario-based analyses conducted by Liu et al. [11] showed that remanufacturing was not always the preferred option. Hence, an environmental assessment is needed before starting a remanufacturing initiative. Information obtained in evaluating remanufacturing initiatives can be valuable in providing a foundation assessment for policymakers and manufacturers to make informed choices and to focus on the improvements in life cycle impact [12].

Peng et al. [13] emphasized the fact that comparative LCAs on new and remanufactured products would advance the understanding of the environmental advantages of remanufacturing. Furthermore, the choice of LCA methodology has a significant influence on the assessment results, Martin et al. [14] confirmed the sensitivity of the assessment results to the methodological choices, where the lifetime of the products, data choices, and other user-related variables for the use of the products had a significant influence on the results. In their study, Chen et al. [15] confirmed the need for the LCA method to be used to evaluate the environmental burden and benefit of recycling. The necessity of following a life cycle assessment (LCA) model was demonstrated by [16] through the development of the LCA model to investigate the energy savings and pollution prevention that are achieved in the United States through remanufacturing a midsized automotive gasoline engine compared to an original equipment manufacturer manufacturing a new one

Rosenthal et al. [17] indicated that they were not able to include air conditioners in their study due to the lack of literature on AC remanufacturing. The study revealed the need for further research on AC remanufacturing and its environmental assessment. It can be concluded that the literature lacks studies that have analyzed the performance of AC remanufacturing. Although the focus of this study was on the environmental performance, other aspects of AC performance are not found in the literature nor are studies that have addressed the economic, technical, or societal aspects of AC remanufacturing. This study seeks to bridge this gap in the literature regarding the lack of the environmental assessment of AC remanufacturing.

3. Methods

Currently, there is no existing plant that produces remanufactured ACs. The remanufacturing plant was designed in this research based on the standard definition in the literature and input from the industrial partner. Note that the steps of the remanufacturing process are well-defined in both the literature and industry. The BS 8887-220 [18] definition as well as definitions from other studies (see Section 2) were adopted to identify the required steps in remanufacturing an EOL AC. Discussion with the industrial partner helped in deciding on the process parameters. It also clarified the ambiguities and helped to choose among the alternatives. The life cycle phases of the remanufactured AC are shown in Figure 1. The process starts with end-of-life AC collection, then the collected products are disassembled into separate components. The disassembled components go through thorough a cleaning process that brings the 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 conducted for a new AC. The storage and distribution of remanufactured AC is identical to the new AC. The following subsections explain the identified steps in AC remanufacturing, and also demonstrates its life cycle inventory. The process parameters and assumptions are listed along each step where these assumptions are made.

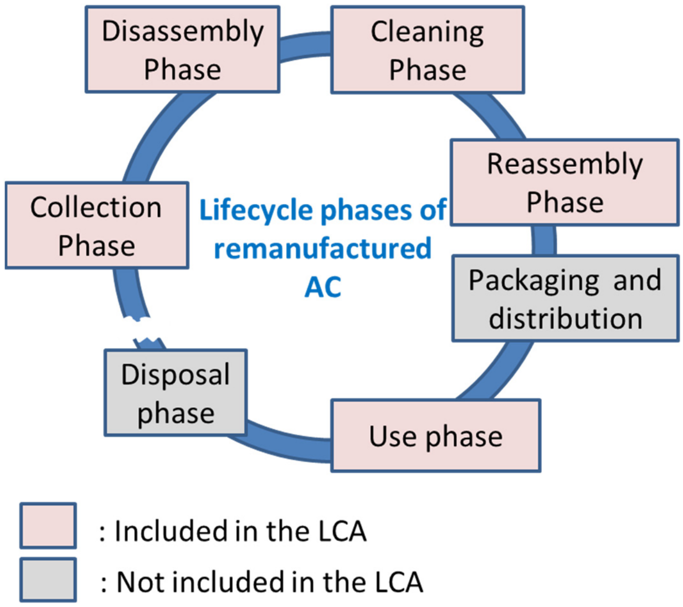

Figure 1. The life cycle phases of the remanufactured AC.

3.1. Data Collection

3.1.1. Measured Data

Measured data were taken from the industrial partner plant as well as from the reverse engineering analyses and measurements conducted off site in the product design lab at our research institution. Examples of the collected data were: bill of material, material composition, weights, dimension, manual and powered equipment, power consumption, etc.

3.1.2. Calculated Data

Data were calculated or directly collected from the published literature or public databases.

3.1.3. Estimated Data

Whenever data cannot be measured or calculated, an expert estimation was sought from the subject matter specialists

4. Results and Discussion

The implementation of the method demonstrated in Section 3 led to the results below.

4.1. Collection Phase

The EOL ACs were collected from a drop off point (collection centers) that covers the whole of the 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; this decision could be either economically or environmentally driven. Collection from a distant location could lead to an increase in the environmental impacts due to long distances between the collection center and remanufacturing plant.

This phase also includes 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; and (3) operation inspection.

In the first stage, a visual inspection is conducted where the units are examined visually. All of the initial observations are noted and written down. In this procedure, the decision of whether the unit is sound enough for remanufacturing or not is based on the opinion of the inspector. Units with the least 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 in this phase is conducted through visual inspection. Finally, in the third stage, units are put under usual operational conditions where they are actually plugged in a power source and put to work. In this phase, the soundness of the unit is judged by the inspector based on how well the unit is functioning.

When considering the design parameters and assumptions, there must be a determination of the process parameters and of the collected data. Collection of the units is conducted using trucks that run on diesel from major cities in KSA, where there are the largest numbers of AC users in the country. The remanufacturing plant is assumed to be in Dammam city, where new ACs are currently manufactured. Table 1 shows the transportation distances between major cities from which the ACs are collected to where they would be delivered at the remanufacturing plant. Distances were obtained from Google Maps. The number of the expected EOL AC units was estimated based on the population density of each city. The number was calculated by taking the city's population times as a ratio defined as:

Ratio = Number of AC unit in use/KSA population
= 3.3 million/27 million = 0.122

Table 1. The distances between the major KSA cities and remanufacturing plant.

City	Distance in km	Population in Millions	AC Unit in Millions	(AC Units)·(Distance)
Mecca	391	5.18	0.633111	247,546,444
Riyadh	1370	3.43	0.419222	574,334,444
Abha	1281	1.53	0.187	239,547,000
Jeddah	1237	1.1	0.134444	166,307,778
Dammam	50	0.9	0.11	5,500,000
Jizan	182	0.66	0.080667	14,681,333
Madinah	1180	0.57	0.069667	82,206,667
Tabuk	1667	0.51	0.062333	103,909,667
Total			1.696444	1,434,033,333
Weighted average distance = 845.3 km				

The weighted average was used to calculate the average distance travelled by a unit of collected ACs. This was found to be 845.3 km per collected unit.

In a life cycle inventory, the collection phase consists of two major processes: transport and inspection. Since inspection is conducted 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 for a distance of 845.3 km. The collection phase was modeled using GaBi software, and the life cycle inventory was obtained based on the modeled phase, which is shown in Figure 2. The detailed inventory can be found in GaBi's professional database.

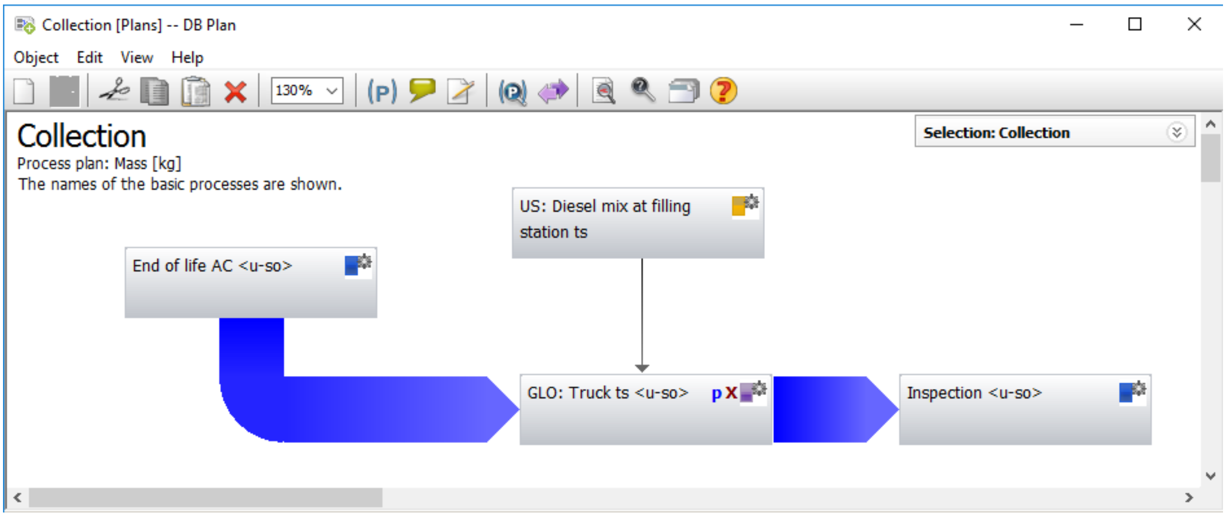

Figure 2. The collection phase modeling using GaBi.

4.2. Disassembly Phase

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 abovementioned. 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 types of screws that fasten the case to the base and other frontal parts; this involves a tool change. Second is the recovery of the refrigerant that is running in the AC unit. This is collected in safe containers for later disposal according to 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. Third, 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. 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.

In the design parameters and assumptions, the majority of the disassembly steps are conducted manually. However, in some steps, machines/tools are needed. The assumptions for the disassembly are as follows:

- Angle grinder tool with a rated power 1000 watt is used to cut the piping or any other rusty parts;
- Handheld power screw driver with a rated power 1000 watt is used to unscrew the screws that fasten the case to the base and other parts;
- Angle grinder cutting time is measured to be 5 min. This is enough time to release all of the pipe connections;
- Unscrewing task is measured to be 30 min for the studied product. High variation in unscrewing time is expected.
- The total electrical power consumption is calculated as a summation of the power needed for unscrewing $\left(30\text{ min} \times \frac{1\text{ h}}{60\text{ min}} \times 100\text{ W} = 500\text{ Wh}\right)$ and pipe cutting $\left(5\text{ min} \times \frac{1\text{ h}}{60\text{ min}} \times 100\text{ W} = 83\text{ Wh}\right)$. The total power is 583 Wh.

- Unwanted parts are scrapped according to environmental regulations and guidelines. They go through material recycling. Their environmental impact was not considered under this study as the process is out of the remanufacturer's control.

In the life cycle inventory, the disassembly process is modeled by using GaBi software. Figure 3 shows the processes of this phase. The LCI of this phase is mainly due to the electricity consumption in the pipe cutting and unscrewing stages. The 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 detailed inventory can be found in the GaBi professional database.

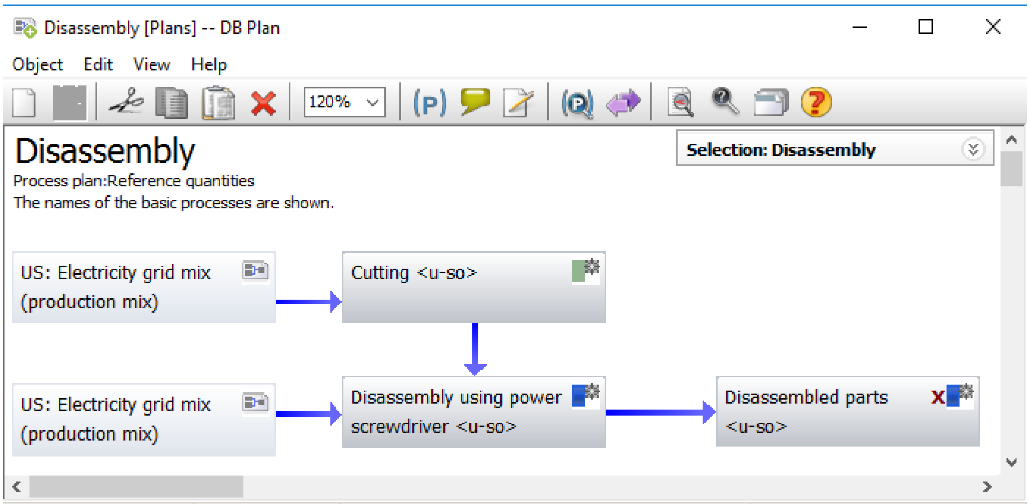

Figure 3. The disassembly phase modeling using GaBi software.

4.3. Cleaning Phase

Due to the extensive usage of the units over a long period of time, there is an accumulation of dirt and biological matter that accumulates on various parts of the AC unit, and thus cleaning of the parts of the unit is imperative. 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 4. During the cleaning process, AC parts are put on a conveyor and are then moved to the various cleaning sections. In the first phase, 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 the cleaning of parts with hot steam wherein steam is blasted on the parts to clean them. Finally, all parts are dried using compressed air, so that they are ready for the next step.

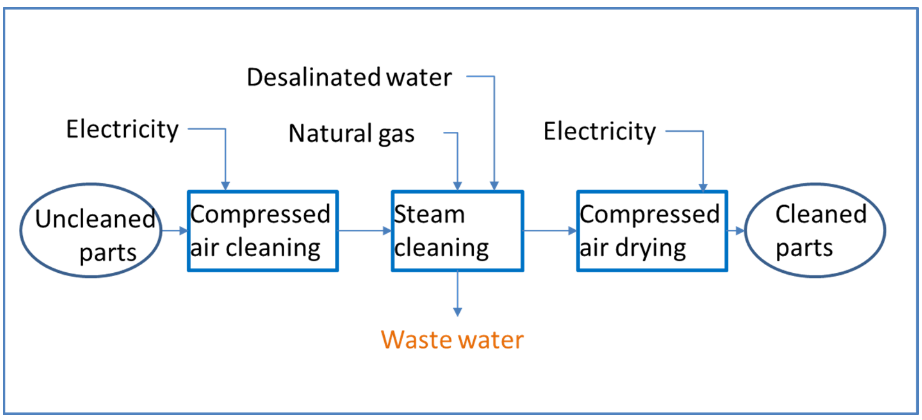

Figure 4. The processes of the cleaning phase.

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 the cleaned parts ready for testing and reassembly. Steam cleaning produces waste water that can be directly connected to the municipal sewage system for further treatment.

The design parameters and assumptions of this stage involve, as mentioned earlier, the cleaning process. This is executed on each separate part of the remanufactured AC. The following provides the details of each stage of the cleaning process, along with the assumptions regarding each single stage.

Compressed air cleaning:

In this stage, the parts are cleaned with compressed air that flows at 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 = (60 × π × d2 × V)/4 = 0.1387 Nominal m^3/s.
- Energy consumption is calculated (0.059 MJ) based on the energy consumption of the selected air compressor.

Steam cleaning:

In this stage, the parts are washed using steam to remove any residual dirt and mud. The process design parameters and assumptions are as follows:

- A pump of a power rating of 7.5 KW and provides a flow rate of 1000 L/h is used;
- Parts of each AC unit require 5 min cleaning with steam;
- Power consumption is 0.625 KW per cleaned part.

Compressed air drying:

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 0.118 MJ and 0.277 Nm^3 respectively.

Material handling:

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

The assumptions for the material handling throughout the processes are listed below:

- The cleaning stages are separated by a distance of 5 m;
- The four conveyors used are 5 m long;
- The conveyors are run on a 1 hp motor and provide a speed of 0.2032 m/s for each unit;
- Energy consumption is calculated (0.07345 MJ).

The total life cycle inventory of this phase comes from the process's individual LCI, which 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 will be the same. Only the quantity will be 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 are not traced back to their sources and the processes that produce them; only the direct input/output of the processes are considered in the LCI. A detailed inventory can be found in the GaBi professional database. The generated LCI is based on the model shown in Figure 5, and the model was constructed using GaBi software.

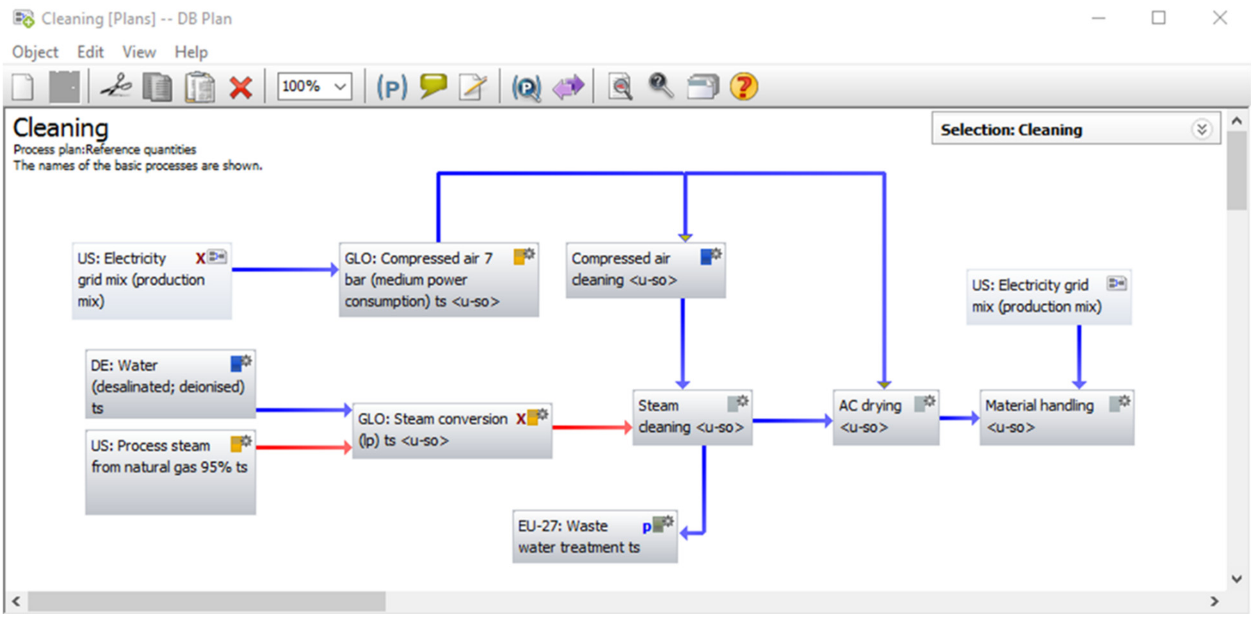

Figure 5. The cleaning phase modeling using GaBi software.

4.4. Reassembly Phase

The following section presents the description of the reassembly phase. This phase starts by verifying the quality of the recovered parts. Both inspection and testing are conducted on all parts before they are placed in reassembly. Once the parts pass the inspection process, they then go on to the next step in the reassembly phase. Failed parts as well as parts that need upgrading are replaced with new ones. Figure 6 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, which are:

1. Assembly of the evaporator and condenser to the base;
2. Assembly of the motor and fans;
3. Assembly of the compressor;
4. The brazing and welding of pipes and joints;
5. Assembly of the front electrical panel along with the wiring;
6. Refrigerant charging.

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). Additionally, as the dimensions and sizes of the units are different due to the different types of ACs, the assembly process is conducted manually with the aid of power tools. These tools are different to those used for new ACs. Tools that are necessary to finish the assembly include:

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

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 ACs can be used in the case of remanufacturing. Finally, a roller conveyor is needed to facilitate the moving of units after they are assembled since the process is manual.

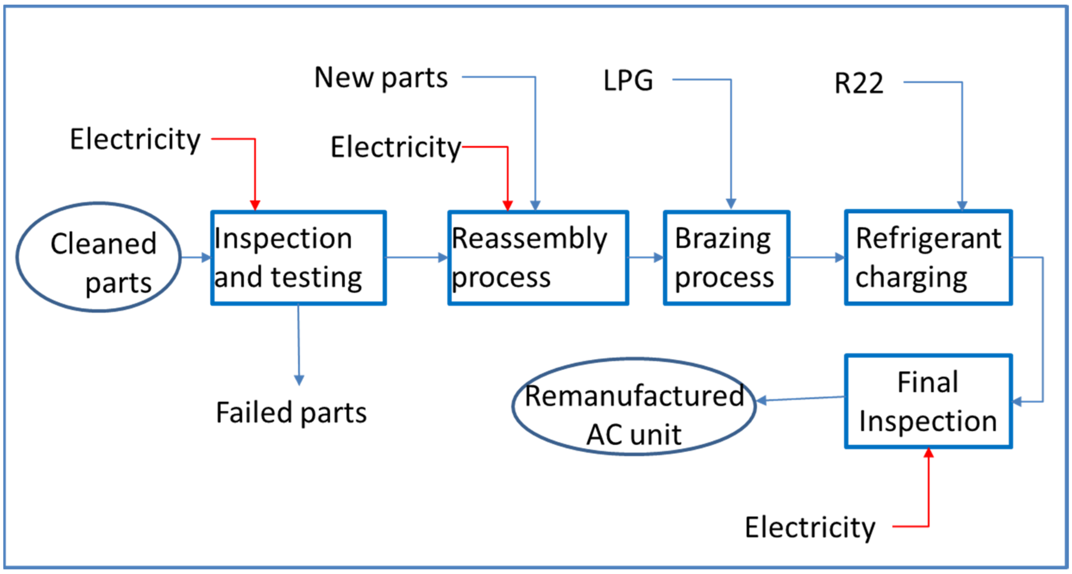

Figure 6. The processes of the reassembly phase.

The design parameters and assumptions for this stage are as follows: after the parts are cleaned, they are put together to be ready to be sold again, and all of the parts need to be inspected and tested as discussed in the following section:

- Visual inspection, wherein the inspector visually investigates each component for apparent damage, cracks, or inconsistencies. 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 the compressor, evaporator condenser, and pipes.

Reassembly can be facilitated using a power screwdriver. The same type of powered screwdriver that is used in the disassembly is used for the reassembly, hence the 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 the 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, which was estimated at 0.001 MJ.

In the stage of refrigerant charging, an R22 refrigerant is charged to the unit. The unit was connected to a reservoir of R22 at a particular pressure. Charging lasts until the pressure in the reservoir and the AC unit become equal. The studied model requires 1 kg of refrigerant. In the case a new type of refrigerant is used, the charged mass needs 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 s and so the power consumption is 0.16 kWh. During the test, the R22 detector is manually used to detect any leak in the whole system.

The total life cycle inventory of this phase comes from its individual processes' LCI, which 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 the GaBi model, as shown in Figure 7. The electricity used to perform the part inspection, reassembly, and final product testing is generated from the same source, so it is expected to generate the same type of inventory, so the difference is only in the generated quantities of each process.

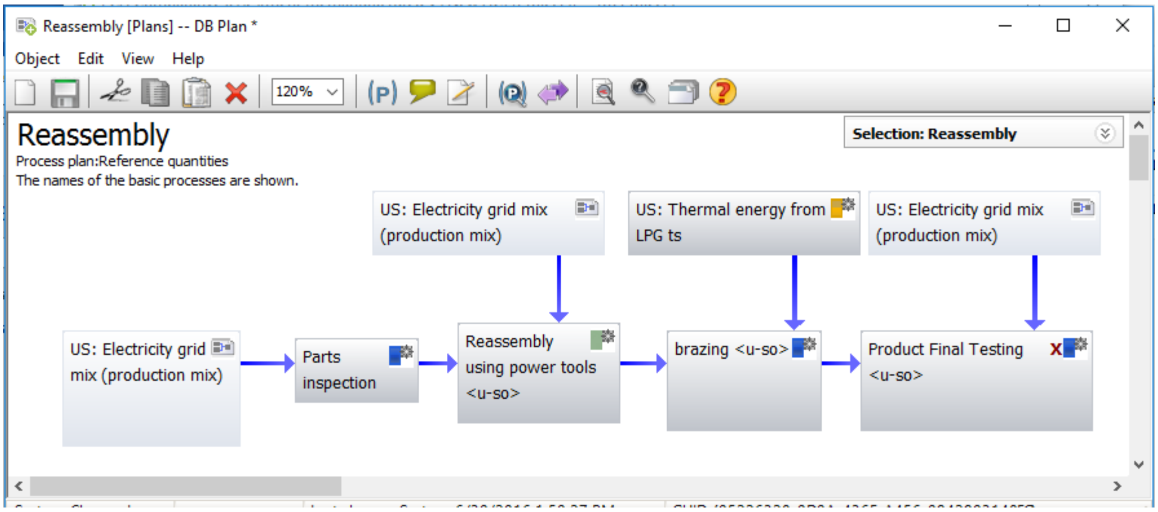

Figure 7. The reassembly phase model using GaBi software.

Table 2 shows the sample LCI for the LPG consumed in the brazing process. A detailed inventory associated with each process in the reassembly phase can be found in the GaBi professional database.

Table 2. The sample LCI for the LPG consumed in the brazing process.

Input Flow	Quantity	Unit	Origin
Air (Renewable resources)	0.4287751	kg	(Calculated)
Antimony (Non-renewable elements)	3.55×10^{-16}	kg	(No statement)
Barium sulphate (Non-renewable resources)	4.48×10^{-16}	kg	Literature
Basalt (Non-renewable resources)	4.29×10^{-10}	kg	Calculated
Crude oil (in MJ) (Crude oil (resource))	1.0336197	MJ	(Literature)
Output Flow	Quantity	Unit	Origin
Thermal energy (MJ) (Thermal energy)	1	MJ	Literature
High radioactive waste (Radioactive waste)	2.58×10^{-9}	kg	Literature
Low radioactive wastes (Radioactive waste)	4.61×10^{-8}	kg	Literature
Medium radioactive wastes (Radioactive waste)	2.33×10^{-8}	kg	Literature
Radioactive tailings (Radioactive waste)	2.08×10^{-6}	kg	(Calculated)

4.5. Use Phase

The following is a description of the use phase. The operating conditions of the remanufactured ACs are identical to the ones for the new ACs. The useful life for the remanufactured AC is also identical to the new AC. Five years of useful life is assumed for the sake of comparison; usually ACs last longer. Five years of useful life was selected because it is the usual warranty time for an AC. The actual consumption of electricity of an AC depends on the operating environmental conditions as well as the efficiency of the AC unit itself.

The following are the design parameters and assumptions. Remanufacturing is usually utilized to upgrade a recovered product. In this study, it was assumed that the remanufactured AC does not undergo any upgrade. The remanufactured AC with no upgrade is the basis for comparison with the new AC. If the remanufactured unit goes through an upgrade, the results obtained in this study might be not valid, thus the impact of the upgrade added to the unit should be considered. The assumptions for the use phase are as follows:

- Compressor power rating 1.75 KW;
- Operating hour per day is 16 h;
- Useful life is 5 years;
- The total energy consumption per year is 1.75 × 16 × 365 = 10,220 kWh;
- The total energy consumption over five years is 10,220 × 5 = 51,100 kWh.

The life cycle inventory is described in the following section. The only input in the use phase is the 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 was built based on a process that generates electricity from natural gas. GaBi software was used to model the use phase, as shown in Figure 8. A detailed inventory can be found in the GaBi professional database.

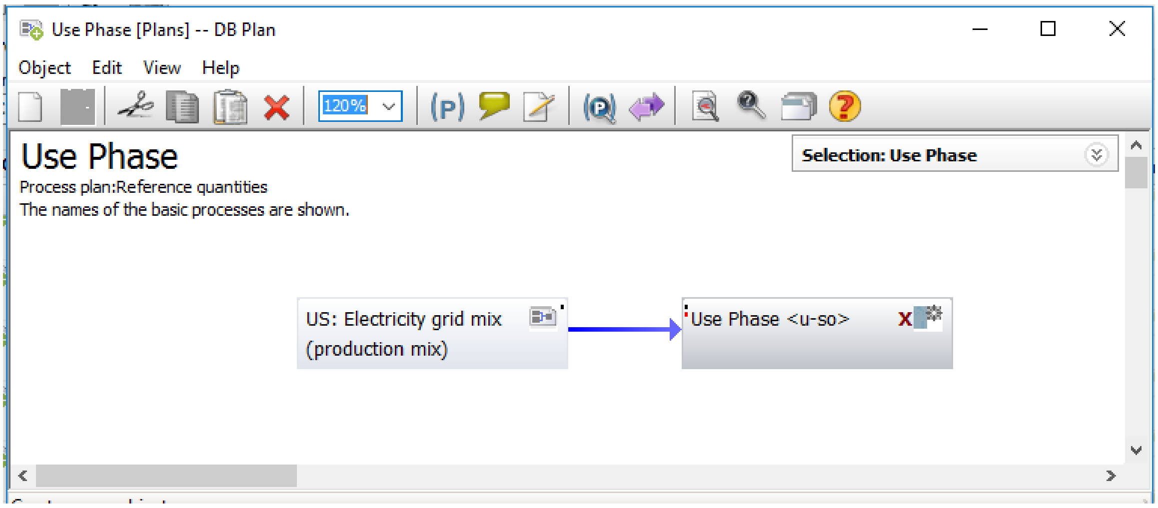

Figure 8. The use phase model using GaBi software.

The LCI for the disposal phase was not considered in this study, since both the remanufactured AC and the new AC have the same 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 section, the impact assessment was conducted using GaBi software, which uses assessment methodologies commonly found in the literature.

5. Conclusions

This research provides a successful and comprehensive approach to identifying the environmental inventory of the AC remanufacturing process. The life cycle approach was found to be accurate and efficient in dealing with this research query. This research conducted a life cycle environmental inventory assessment of a remanufactured AC. ISO 14,044 was used to guide the assessment process. It was found to be useful and helpful toward the achievement of the research objectives. The following conclusions can be drawn based on the conducted research:

- The life cycle approach was found to be 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 the saved material and parts during the manufacturing phase. The assessment should be extended to include a complete life cycle, which was the approach followed in this research project
- 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.

- Environmental impact software was found to be an efficient and accurate tool to conduct the inventory analysis.
- The developed life cycle model, with the help of GaBi, was 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 to make informed decisions.
- A new business model, based on a 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.

The environmental inventory was found to be highly dependent on the choices of machines and the methods of performing the activities of remanufacturing. Hence, process designers should consider environmentally friendly choices when they design a remanufacturing process.

Author Contributions: Conceptualization, A.Z., M.A., A.E.E.A.E. and B.S.; Methodology, A.Z., M.A. and B.S.; Software, A.Z. and M.A.; Investigation, A.Z. and A.E.E.A.E.; Resources, A.Z., M.A. and B.S.; Data curation, A.Z. and A.E.E.A.E.; Writing—original draft preparation, A.Z., M.A. and B.S.; Writing—review and editing, A.Z. and B.S.; Project administration, A.Z., M.A. and B.S.; Funding acquisition, A.Z., M.A. and B.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Plan for Science, Technology, and Innovation (MAARIFAH), King Abdulaziz City for Science and Technology, Saudi Arabia, under Award 15-ENE4953-02.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All of the data are presented in the manuscript; for further information, please contact the corresponding author.

Acknowledgments: The authors would like to thank the National Plan for Science, Technology, and Innovation (MAARIFAH), King Abdulaziz City for Science and Technology, Saudi Arabia, for funding this work under Award 15-ENE4953-02.

Conflicts of Interest: The authors declare no conflict of interest.

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