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CASE STUDY

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A comparison of repaired, remanufactured and new compressors used in Western Australian small- and medium-sized enterprises in terms of global warming

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Abstract

Repaired compressors are compared with remanufactured and new compressors in terms of economic and environmental benefits. A detailed life cycle assessment has been carried out for compressors under three manufacturing strategies: repaired, remanufactured and new equipment. The life cycle assessment of the global warming potential of repaired compressors varies from 4.38 to 119 kg carbon dioxide equivalent (CO_2-e), depending on the type of components replaced. While greenhouse gas emissions from the remanufactured compressors (110 to 168 kg CO_2-e) are relatively higher than those from the repaired ones (4.4 to 119 kg CO_2-e), a new compressor has been found to produce a larger amount of greenhouse gas emissions (1,590 kg CO_2-e) compared to both repaired and remanufactured compressors. Repairing failed compressors has been found to offer end users both dollar and carbon savings in contrast to remanufactured and new compressors. The research also found that extended lifetime is more important than the manufacturing processes in terms of greenhouse gas emissions. Since a remanufactured compressor offers a longer life than a repaired compressor, the replacement of the latter with the former can avoid 33% to 66% of the greenhouse gas emissions associated with a new compressor production with a lifetime of 15 to 25 years.

Keywords: End-of-life product, Life cycle assessment, Global warming

Introduction

This paper compares the economic and environmental implications of repaired, remanufactured and new compressors. It focuses on refrigeration and air-conditioning compressors.

With the increase in the world's consumption of household and industrial products, there is a need to reduce the consumption of mineral resources and the amount of waste generated and end-of-life products sent to scrap yards. To implement this resource efficiency objective, recoverable manufacturing systems could be used. These include repair and remanufacturing, which differ in key control aspects [1]. From ACDelco's experience in Australia, repairing time-consuming and expensive task than completely stripping the engine and then rebuilding or remanufacturing it [2]. For customers, the availability of remanufactured goods means more uptime for their products, which translates into significant production and financial benefits. For some existing manufacturers, the economic efficiency of remanufacturing is clear, and it has become a widely held assumption that such systems would also be more eco-efficient [3].

By utilising recovered end-of-use products and parts, remanufacturing could reduce the manufacturing and disposal costs of heavy and material-intensive industrial machinery and electronic equipment [3-6]. In a carbon-constrained economy, it would be useful to work out the carbon-saving benefits of the replacement of an original equipment manufacturer (OEM) product with a remanufactured one. OEM refers to the company that makes a product using original parts and virgin materials.

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Life cycle assessment (LCA) has been widely used to analyse the environmental benefits of the replacement of a new product with an end-of-life product for internal combustion engines, electrical appliances, gear boxes and compressors [7-10]. The most detailed LCA remanufacturing study in Australia to date was on the remanufacturing of photocopiers at Fuji Xerox and of a compressor at Recom Engineering [2,11].

The environmental impact of options following a machinery failure needs to be assessed in order to reduce emissions from the manufacturing sectors. These options can either be repairing or replacement with an OEM or remanufactured machinery. In addition to the energy and materials required for repairing, remanufacturing and the production of new machinery, the end-of-life situation could affect the life cycle environmental performance of these options. However, so far, the literature reviewed did not estimate the environmental advantages of remanufacturing over repairing in Australia and elsewhere. The environmental performance of repair and remanufacturing was thus carried out by a detailed LCA.

This paper provides options for choosing repairing, remanufacturing or purchasing new compressors to reduce the carbon price. It demonstrates that a repaired compressor can perform as well and as long as remanufactured and new compressors within the first 3 years of the compressor's life. Performance depends on the type of fault in the air-conditioning compressors and on the repairs being of the highest quality.

This research considers a ‘cradle to gate’ assessment of compressors for a Western Australian small- and medium-sized enterprise. This means that the LCA does not take into account product use and disposal, including factors such as recycling and recovery, which would offset carbon emissions and hence the carbon price. The LCA includes only global warming impacts which can be directly attributed to a repaired compressor and the production of a remanufactured compressor and a new compressor.

Methodology

LCA has been carried out to assess the carbon-saving benefits of a repaired compressor over remanufactured and new compressors.

The LCA follows the ISO14040-43 guidelines [12] in four steps:

1. Goal and scope definition
2. Inventory analysis
3. Impact assessment
4. Interpretation

Goal and scope

The goal of this LCA is to determine and compare the economic and environmental implications of repaired compressors with remanufactured and new compressors. The compressor used in this case study is a 20 HP Bitzer compressor (Bitzer Kühlmaschinenbau GmbH, Sindelfingen, Germany) for refrigeration and/or air conditioning. This paper determines the difference in the carbon footprint (greenhouse gas (GHG) emissions) associated with repairing compressors and remanufacturing them. These results will also be compared against the carbon footprint of new (OEM) compressors to demonstrate the carbon and cost savings.

There are some limitations that determine the scope of this LCA. First, the analysis only took into account repairs that are of A+ quality (as good as new with 2 years of product starts). This quality is not always achieved, with some repairs being of lower quality. Second, refrigeration and air-conditioning compressors are inherently reliable and can survive in service for decades. In Recom Engineering's experience, the mean time to failure for a compressor is 15 years. Third, this analysis is only based on the GHG emissions associated with repairing, remanufacturing and producing new refrigeration and air-conditioning compressors. Other than global warming or GHG emissions, no other environmental impacts have been estimated for this LCA.

Life cycle inventory

A life cycle inventory (LCI) considers the amount of each input and output of different stages of a product's life cycle and is a necessary initial step in an LCA. An LCI was constructed that includes all inputs involved in the repairing of a compressor in a specific scenario, where the scenarios vary with the number and type of parts replaced and the type of repairing and machining operations.

The LCA of a repaired compressor is better described as preventative maintenance and/or when the compressor has had a minor failure. After the failed compressor has been cleaned and prepared for repair, the repair process involves replacing the damaged components that were removed during the disassembly stage. These were remanufactured parts (valve plate, terminal block) or new components (oil pump, shaft seal). Table 1 shows the differences between repairing and remanufacturing operations in order to clarify the environmental implications of these recovery or reuse operations.

The benefit of repair is that it is on-site. There is no need to disassemble the compressor and transport it to another location, and this saves time, money and, most importantly, carbon emissions. Repairing a compressor involves the following:

- Inspection and diagnostics: once a failed compressor has been inspected and the unit is deemed repairable, the repair can commence. Inspection and diagnostics are done by hand which can take 30 min to 1 h.

Table 1 Differences between the repairing and remanufacturing processes

Stages	Repair	Remanufacture
Stage 1: disassembly	Disassembly of the faulty component/part is manually done	The whole compressor is stripped down, using an electric- or air-powered rattle gun. The energy used during cleaning and machining is approximately 13.5 MJ
Stage 2: cleaning and washing	Minimal cleaning and washing with repairs done on-site, using a universal cleaning agent (200 mL) to wipe down the surface that is being repaired	Most components, as they are reused, are thoroughly cleaned and washed with a variety of chemicals, using approximately 10.5 MJ
Stage 3: machining	There is usually no machining during a repair, depending on the part; in some cases, valve plates need to be remanufactured, requiring only minor cleaning, washing and surface grinding (4.23 MJ)	Parts that can be remanufactured and reused are often machined to ensure that they are useable; machining includes polishing, surface grinding and rewinding, using a total energy of 114.8 MJ
Stage 4: part replacement	Components are usually replaced as necessary with new parts during repairs	Most components are reused, and components that are worn out are replaced with new components
Stage 5: assembly	Reassembly is on-site using hand tools or manual labour	All components are reassembled using an air gun and hand tools, using 13.5 MJ

The data on energy consumption were obtained from Recom Engineering, Perth, Western Australia.

- Part disassembling: after inspection, the faulty part is detached from the compressor using hand tools which can take 1 to 2 h.
- Minor cleaning and washing: the faulty part or component is removed and cleaned to remove any dirt and debris. Universal flushing agents are used for the cleaning of the compressor and for the remanufacturing of valve plates and terminal blocks. Chemicals such as alkalis, phosphoric acid and decarboniser are mixed with hot water for cleaning and washing operations.

Repairing involves machining a part or component to be remanufactured. For example, in 80% of cases, valve plates are remanufactured which requires cleaning and then removing the broken reeds. The valve plate is then machined using a surface-grinding machine.

Part reassembling involves simply reassembling the compressor with a new part or a remanufactured valve plate or terminal block. This is done with hand tools or an electric impact gun. On the other hand, remanufacturing a compressor involves disassembling, cleaning and washing (C&W), machining operations, replacements, assembly and testing [11].

Figure 1 shows a detailed version of the LCI of a repaired compressor. It shows the inputs and outputs associated with the processes and the steps that a failed compressor goes through to be returned to service.

Life cycle impact assessment

The carbon footprint of a repaired compressor has been measured in terms of GHG emissions. From the energy and material data in the LCI, the GHG emissions have been calculated and converted to carbon dioxide equivalent (CO_2-e). Simapro 7.2 software [13] has been used to calculate these GHG emissions from paired compressors. The result is also compared with the carbon footprint of remanufactured and new compressors [11]. The input and output data of different stages from the LCI were used in the Simapro 7.2 software. This allowed the GHG emissions to be calculated for the repair of refrigeration and air-conditioning compressors. These inputs and outputs are linked to relevant Simapro 7.2 libraries which are databases of energy consumption, emission and material data for the production of one unit of a product. The units of input and output data from the LCI depend on the units of the relevant emission database in the software or its libraries [11].

Since local chemicals were used for cleaning and washing, the libraries from the Australian LCA database [14] for these chemicals were used for the analysis. The main chemicals used were phosphoric acid, thinner, decarboniser, alkali and penetrene. Phosphoric acid was available on the Simapro 7.2 databases, whereas sodium carbonate (alkali), thinner (methyl ethyl ketone) and decarboniser (dimethlamine) were obtained from the ecoinvent database [15] because they were unavailable in the local database [14]. Penetrene is used in both repairing and remanufacturing, and its data were available neither on the Simapro 7.2 database nor in the literature. Penetrene is comprised mainly of petroleum distillate and tetrachloroethylene, so the energy consumption values of these chemicals were used to estimate the approximate emission factor of penetrene.

Recom Engineering is a Western Australian company which disassembles, cleans, washes, machines, reassembles and tests parts and equipment. Therefore, the Western Australian electricity mix has been considered for calculating GHG emissions. Repairing requires the replacement with new components, and so, the emissions for the production of these new parts were estimated by summing all GHG emissions from mining, processing, foundry and

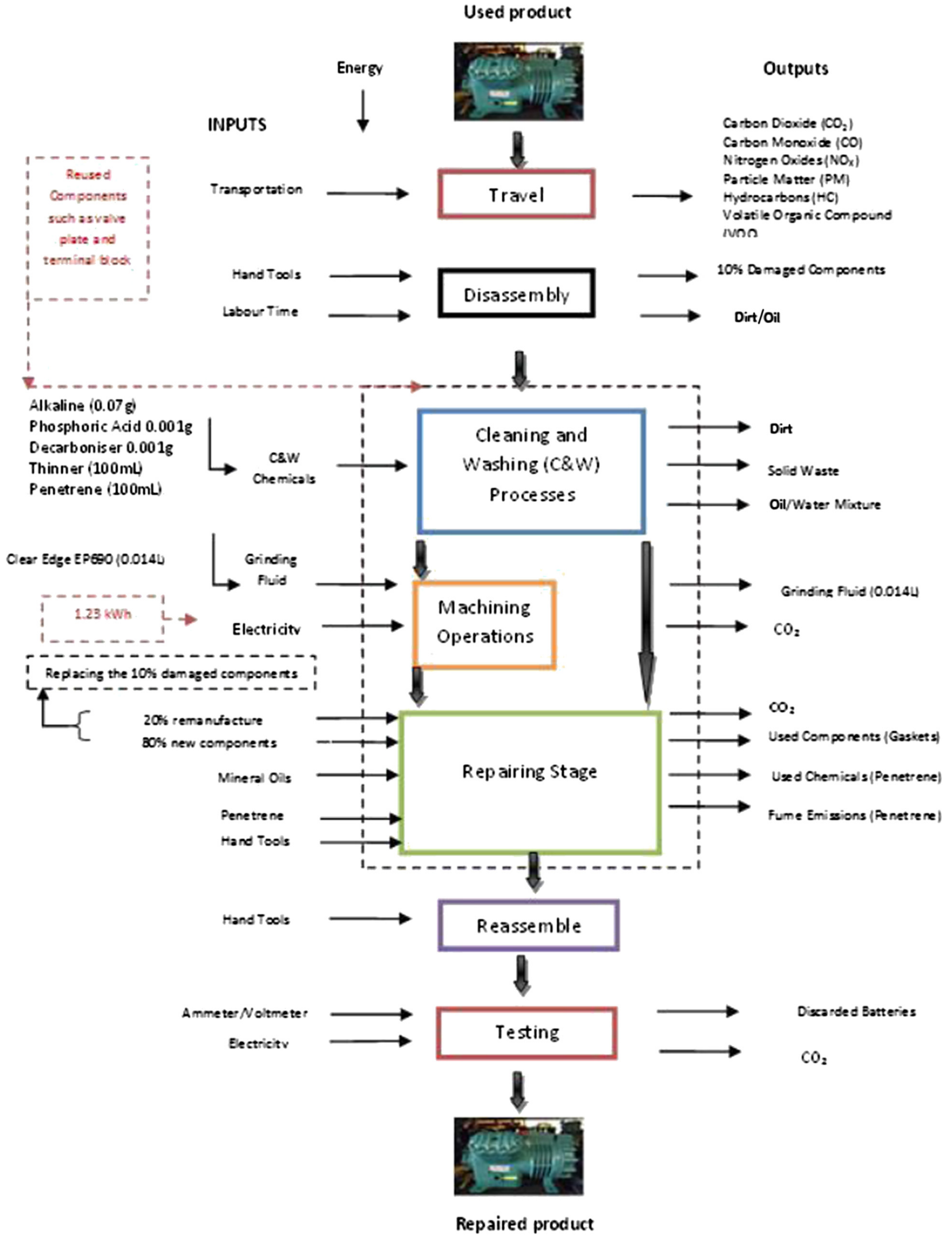

Figure 1 Detailed life cycle inventory for repaired compressors.

assembling processes. Transport is done using a truck and van with an average distance of 100 km. The unit for transport is tonne-kilometre travelled.

Results and discussion

Carbon-saving benefits of the replacement of remanufactured and new compressors with repaired compressors

Firstly, the carbon-saving benefits have been calculated for the following scenarios:

- Scenario 1: repairing with valve plate replaced
- Scenario 2: repairing with oil pump replaced
- Scenario 3: repairing with terminal block replaced

The carbon footprints of repaired compressors are 4.4, 6.7 and 119.5 kg CO_2-e for the three scenarios, respectively. Scenario 3 produces 12 and 27 times more GHG emissions than scenarios 1 and 2, respectively. This is because the valve plate that was replaced with the new one in scenario 1 was comprised of stainless steel, which is a very energy-intensive material consuming 108 times more energy than normal steel (Figure 2).

The carbon footprint of the same-size (20 HP Bitzer) repaired semi-hermetic reciprocating compressor was compared with the carbon footprint of a remanufactured compressor and a new compressor [11]. The production of a new compressor would result in a total of 1,590 kg CO_2-e, while the remanufactured one would produce 110 kg CO_2-e in remanufacturing scenario 1 and 168 kg CO_2-e in remanufacturing scenario 2 [11].

Table 2 shows that GHG emissions could be mitigated by the replacement of remanufactured and new compressors with a repaired compressor. The repaired compressor in scenario 1 produced 29% and 92.5% less GHG emissions than the remanufactured compressor in remanufacturing scenario 2 (with 96.5% of total parts reused) and a new compressor, respectively, but produces 8% more GHG emissions than remanufacturing scenario 1 (with 99% of the total parts reused). As explained before, the replacement of a valve plate with the new one, which is made of energy-intensive stainless steel, increased the GHG emissions significantly. The repaired compressor in scenario 2 (with oil pump) has produced 94%, 96% and 99.6% less GHG emissions than those in remanufacturing scenarios 1 and 2 and new compressor production, respectively. The repaired compressor in scenario 3 can mitigate 96%, 97.4% and 99.7% of the total GHG emissions by replacing remanufacturing scenarios 1 and 2 and the production of a new compressor, respectively. Thus, repairing is less energy intensive and produces lower GHG emissions compared to remanufacturing or the production of new compressors.

In remanufacturing scenario 1 (minimum part replacement), 99% of the parts (on the basis of weight) were reused by cleaning, washing and machining, and less than 1% were replaced with new parts.

In remanufacturing scenario 2 (maximum part replacement), 96.5% of the total parts were reused, and the rest were replaced with new parts.

When the use (or operation) stage is included, the additional GHG emissions would be 189,000 kg CO_2-e, which is significantly higher than the emissions from the manufacturing stage. In most of the repairing of the compressor, replacement accounts for a significant portion of the total emissions, followed by repairing and machining. For scenario 1, 95%, 3% and 2% of the GHG emissions result from replacement, machining and repair, respectively. These values for scenario 2 are 62%, 20% and 18%, respectively. For scenario 3, 49%, 30% and 22% of the total GHG emissions result from replacement, machining and repair, respectively. Therefore, replacement needs to be avoided, especially for high-energy-intensive materials - those associated with the processing and manufacturing of the valve plate. In all

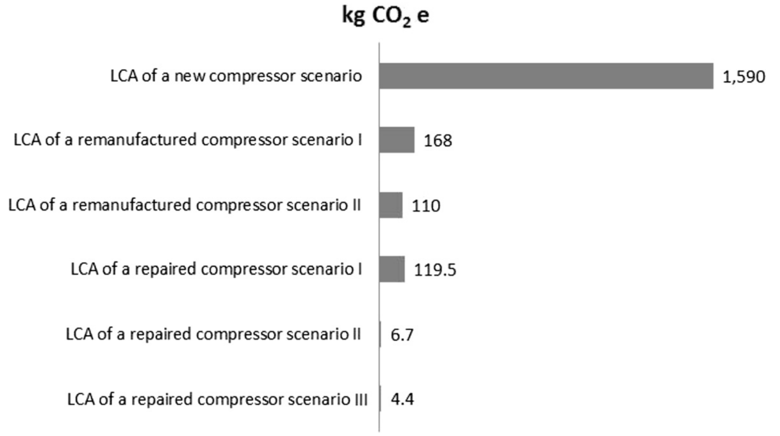

Figure 2 The carbon footprint of repaired, remanufactured and new compressors.

Table 2 GHG emission mitigation due to the replacement of remanufactured and new compressors with repaired compressors

Repairing scenario	GHG emission mitigation by the three repairing scenarios (%)		
	Remanufacturing scenario 1	Remanufacturing scenario 2	New
1	−8	29	92.5
2	94	96	99.6
3	96	97.4	99.7

Remanufacturing scenario 1 (99% of the parts were reused and 1% were replaced with new parts) and scenario 2 (96.5% of the parts were reused and the rest were replaced with new parts (3.5%)) were extracted from the work of Biswas and Rosano [11].

cases, machining and repairing produce a very small portion of GHG emissions compared to replacement.

Economic benefits

Since repairing emits less CO_2-e, the carbon tax will be reduced in the current Australian carbon pricing scheme. If the price of carbon were set at Australian $25 per tonne of CO_2-e, a new compressor which emits 1.590 tonnes CO_2-e equates to an additional cost of Australian $39.75. Repairing scenarios 1, 2 and 3 would have an additional cost of Australian $2.98, $0.20 and $0.10, respectively. Remanufacturing scenarios 1 and 2 have an additional cost of Australian $2.75 and $4.20, respectively. In the case of a 20 HP Bitzer semi-hermetic reciprocating compressor, the estimated cost of repaired compressors (Australian $1,000) is 73% less than that of a remanufactured compressor (Australian $3,752) and 82.4% less than purchasing a new compressor (Australian $5,686) (PF, personal communication).

Implication of the lifetime of compressors in the life cycle assessment

Since the lifetime of a remanufactured compressor is more than that of a repaired compressor (Figure 3), a different conclusion is obtained. Figure 3 was derived by interviewing local users, repairers and manufacturers. It can be seen that the replacement of a repaired compressor with a remanufactured compressor can avoid two thirds of an OEM compressor production over a lifetime of 25 years or one third for a lifetime of 15 years. This shows that the replacement of a repaired compressor with a remanufactured compressor can avoid 33% to 66% of the GHG emissions associated with the OEM compressor production between 15 and 25 years. Therefore, repairing appears to be a carbon emission reduction option, and remanufacture is more like a carbon sequestration option from a long-term perspective.

Conclusions

Repairing as the main option for the management of end-of-life products can help reduce the stress on natural resources and can also be economically and environmentally beneficial. Repairing compressors can potentially reduce the GHG emissions associated with a remanufactured or new compressor. About 29% to 97% of the total GHG emissions can be mitigated by replacing a remanufactured compressor with a repaired compressor, and a maximum of 99% of the total GHG emissions can be mitigated by replacing with a new compressor. Repaired compressors are cheaper than both remanufactured and new compressors

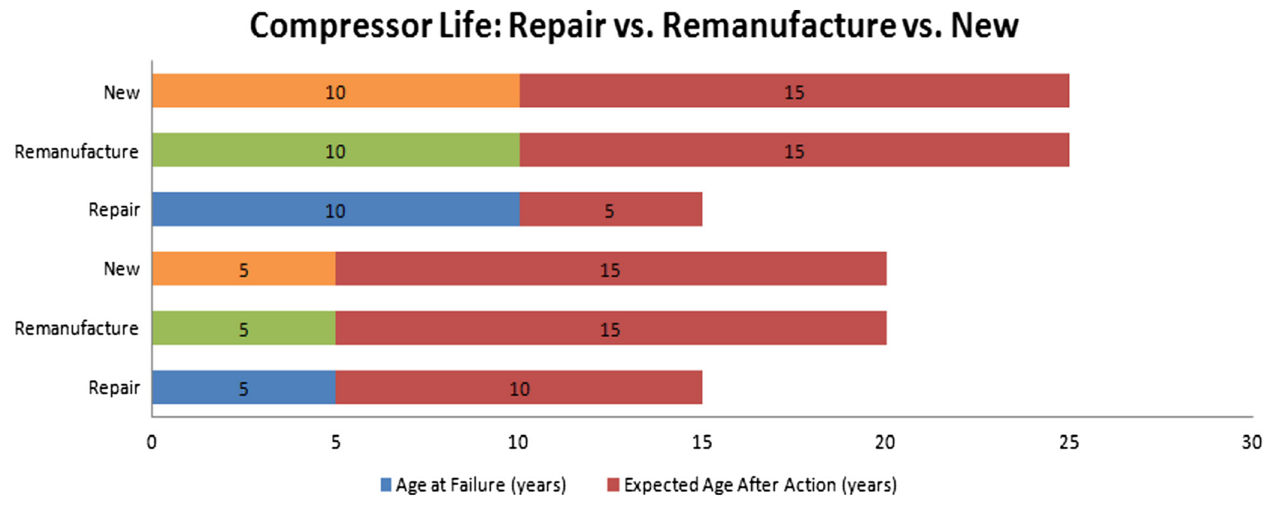

Figure 3 Compressor life and expected life.

and conserve non-renewable mineral resources for future generations.

From a short-term perspective, repairing compressors can potentially reduce the GHG emissions associated with a remanufactured or new compressor. The research also found that lifetime durability matters more than the manufacturing processes. Remanufacturing can offer significant carbon-saving benefits rather than repairing from a long-term perspective. Finally, in the case of either repairing or remanufacturing, it is crucial that the replacement with energy- and carbon-intensive new parts be avoided to increase the carbon-saving benefits.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

WKB carried out the life cycle assessment analysis and completed the manuscript. VD collected data, developed the life cycle inventory and carried out a literature review and analysis. PF provided industry data, technical support and guidance. MNI participated in the review and consultation process. All authors read and approved the final manuscript.

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