Remanufacturing as a means for achieving low carbon SMEs in Indonesia

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Abstract Remanufacturing can importantly reduce the energy intensity and associated greenhouse gas (GHG) emissions and increase the eco-efficiency of product systems by utilising recovered end of life (EOL) parts. This paper presents the GHG mitigation potential of technically feasible remanufactured products in Indonesian small and medium-sized enterprizes (SMEs). Life cycle assessment approach and Weibull ++8 software have been used to calculate environmental and quality parameters. Since existing remanufactured products have not been found to meet the technical criterion for customers' satisfaction, a number of alternative remanufacturing strategies have been explored to identify an option that has not only reduced GHG emissions but also have satisfied reliability, durability and warranty period criterion.

Three improvement scenarios involving three different remanufacturing strategies were investigated in this case study, and yielded useful insights in order to come up with a sustainable remanufacturing strategy. However, the improvement scenario III, which maximizes the use of used components, was found to offer a technically and environmentally feasible remanufacturing solutions. Overall, this research has found that about 7,207 t of CO_2–eq GHG emissions and 111.7 TJ embodied energy consumption could potentially be avoided if 10% of alternators in Indonesian automobile sector are remanufactured using technically feasible remanufacturing strategy.

Keywords Small and medium-sized enterprize, remanufacturing, greenhouse gas, life cycle assessment

Introduction

Asian countries alone contributed two third of the total global GHG emissions (US Environmental Protection Agency 2015). The emissions was increased by 100% (i.e. 406.21 Mt CO_2–eq) during 2000-2010 (US Energy Information Administration 2013) in Indonesia, mainly due to the increase in population and GDP growth. In the case of India, the population is predicted to grow to 1.5 Bn, and GDP to increase to USD 4 tn by 2030, which is in turn predicted to lead to an increase in demand for resources (i.e. coil, oil) and a significant increase in GHG emissions (i.e. 65 Bt) (McKinsey & Company 2014). Also in China, rapid urbanization, population growth and economic development have also created critical environmental problems. In 2010, China recorded the highest GHG emissions globally, associated with fossil fuel combustion, cement manufacturing and gas burning (United States Environmental Protection Agency 2015) .

It appears that Asian countries experience social and environmental problems associated with industry-driven economic activities. There is potential for sustainable manufacturing to reduce GHG emissions, to reduce energy consumption, and to create employment by converting waste or end of life (EoL) products to useful resources or remanufactured products (Ramoni and Zhang 2013). GHG emissions could be reduced to approximately 800,000 t due to reductions in materials and energy consumption (Gray and Charter 2007). Another study reported that the GHG emissions of an automotive engine could be decreased from 15,300 to 11,300 t CO_2–eq through remanufacturing (Liu 2005). Biswas and Rosano (2011) stated that the GHG emissions resulting from manufacturing new compressors could be significantly reduced (by about 89.4–93.1%) by considering remanufacturing scenarios (Biswas and Rosano 2011).

In the case of electronic devices, Kerr and Ryan (2001) found that remanufacturing can reduce resource intensity over the life cycle of a photocopier by up to a factor of 3.1 which in turn can save GHG emissions significantly. On the other hand, the embodied energy consumption can be reduced by 87% (Fatimah and Biswas 2016; isites 2016)

There are material, energy and GHG reduction benefits to remanufacturing activities (Krajnc and Glavic, 2003). It was estimated that the material savings derived from the remanufacturing process are equivalent to 155,000 railways cars crossing 1,100 miles (Giuntini and Gauddette 2003), while remanufacturing activity could also avoid about 420 TJ (Terajoule) of energy consumption per year and mitigate 28 million tons of CO_2. For auto part products, the remanufacturing of bearings could decrease GHG emissions (i.e. CO_2 and SO_2 emission) by approximately 60% (Svenska Kullagerfabriken 2014). By using recovered end of life (EOL) parts, remanufacturing was able to reduce economic costs associated with both the manufacturing and disposal of heavy and material-intensive equipment. Biswas and Rosano (2011) found that the remanufactured compressors are 34% cheaper than a new (OEM) compressor.

This paper uses Indonesian remanufacturing SMEs as a case study for assessing GHG mitigation in Asian countries. Indonesian industry sector is made up of Large Enterprises (LEs) and Small and Medium-Sized Enterprises (SMEs). However, the SMEs accounts for significant portion of Indonesian industry (99.99%) (Tambunan 2006). SMEs accounted for 58.33% of GDP in 2008, and these industries contributed to 16.72% of the total national export. Manufacturing is also one of the main economic supports of SMEs. Environmentally, the manufacturing activities in SMEs contribute greatly to emissions, resource scaricty and inefficient equipment usage (Dhewanthi 2007).

Indonesia has become the largest energy producer and consumer in Southeast Asia (Ardiansyah 2011). However, today energy security issues are Indonesia’s principal challenge and predicted to remain so until 2020 due to the rapid growth of energy consumption which is 50% higher than the consumption over the past decade (Fatimah 2014). Remanufacturing in Indonesian SMEs could be another potential strategy in reducing energy consumption significantly by reducing upstream activities.

Another important reason is that Indonesia is one of the 10 largest GHG-emitting nations in the world. Indonesian GHG emissions were about 1,377 Mt CO_2–eq in 2000, reaching 1,991 Mt CO_2–eq in 2005, and are predicted to increase to 3,078 Mt CO_2–eq in 2020, based on the Second National Communications (Dewi 2010). Manufacturing contributed about 40% of the emissions (Ministry of Finance 2009b); remanufacturing could potentially reduce these emissions.

At the G20 Pittsburg meeting in 2009, Indonesian government has targeted that national GHG emissions can be reduced by 26% of the business as usual (BAU) by 2020 (Ardiansyah et al. 2012). However, the expected increase in energy consumption during this period could increase the GHG emissions significantly. As a result, the GHG reduction target may not be achieved unless radical energy conservation is implemented (Ardiansyah et al. 2012). Remanufacturing could be one of the key strategies to assist in energy savings (Biswas et al. 2011), as manufacturing accounted for 37% of Indonesian energy consumption in 2009 (ABB 2011).

This paper assesses GHG mitigation opportunity by technically feasible remanufactured alternators. This technical feasibility comes first because the existence of poor quality, unreliable, unsafe and non-standardized products with minimal warranties is a common issue among Indonesian SMEs. Insufficient infrastructure, such as electricity, transportation and telecommunications, are other problems which could potentially impede the development of remanufacturing by SMEs (Fatimah et al. 2013).

Firstly, this paper assesses the technical viability and GHG emission and embodied energy consumption saving potential of remanufactured alternators under the existing scenario. Since the existing scenario is not technically feasible, a number of improvement strategies have been proposed that can help remanufacturing industries to achieve technical viability. The improvement of materials (i.e. new material replacement), energy (i.e. optimum energy consumption), technical skills (i.e. training), processes (i.e. safety procedures), equipment (i.e. advanced testing technology), and supply chain (i.e. expansion of the collection area) were investigated to determine technically, and environmentally feasible solutions. An life cycle assessment (LCA) tool has been applied to estimate GHG emissions and embodied energy consumption.

Methodology

This methodology has been designed to assess the carbon saving opportunities through the use of technically feasible remanufactured alternators. Reliability, durability and warranty period are some technical indicators commonly used to ensure the quality of products have been calculated for the current technical analysis. Both technical and environmental indicators have been compared with the threshold values for determining the maximum possible GHG emissions that can be mitigated through the use of technically feasible alternators.

Technical analysis

Reliability: Weibull distribution as a continuous probability distribution model has been widely used for mechanical reliability design and analysis (Liao et al. 2011). This distribution is a handy and adaptable tool to determine the practical results of a reuse strategy (Anityasari

2009). Therefore, Weibull ++8 software was used to carry out the reliability analysis for this current research. The software is made by Reliasoft Corporation (Reliasoft 2013) and was applied in order to generate the reliability plots and to define the reliability distribution and the reliability parameters of the remanufactured products. In addition, the suspension data including suspended time (S) and number of suspension products and the failure data involving time to failure (F) and number of failures were provided to support the calculation. The mathematical formula for the Weibull distribution is explained in following equation where F(t) denotes the probability of units failing and t is the failure time.

$$F(t) = 1 - exp\left[-\left(\frac{t}{n}\right)^{\beta}\right] \quad (1)$$

Where,

n : scale parameter

β : shape parameter (h or y)

t : failure time (h or y)

For example, if remanufactured products are used for 800 h in a year, and the Weibull distribution of the failure is modelled as scale parameter n = 8,000 hours and shape parameter β = 1.5, the probability that the remanufactured products would fail within five years is 0.298 or approximately 30% of overall products.

Next, the reliability prediction was used to determine the reliability of the remanufactured products based on the improvement scenarios. Since the components of the remanufactured alternator have to be changed (reuse, recycle) to improve the quality of the product, both series and parallel systems were used to determine the reliability of the remanufactured products. For the series system, the failure rate depends on the total failure rate of the components, while the failure rate depends on the failure of each component for a parallel system. So the system does not work, if one component in a parallel system fails.

In order to understand the distinction between series and parallel systems, two examples are presented in Fig. 1. Suppose a series system consists of three parts with reliabilities of 0.99, 0.95 and 0.95, and in this case, the reliability of the series system has been calculated as 0.89 (0.99 x 0.95 x 0.95 = 0.89). In the case of a parallel system consisting of three components (reliability = 70% for each), the reliability is estimated to be 0.97 which is calculated from (1-0.3^3). The parallel system works if all of the components work. Theoretically, the overall parallel system will have greater reliability than any of the single components (Romeu 2004). Finally, reliabilities of parallel and series system are multiplied to determine the overall reliability.

Durability : Durability is the probability of a product working properly in a certain period of time. Durability testing is often considered a sub-group of reliability (Sterling Performance 2014). Thus the durability performance is analysed based on the reliability value. Assume that the reliability R(t) of a remanufactured part is 95% for a life expectancy of two years. Accordingly, the durability has to meet the life expectancy of the product which is two years with a reliability of 95%. By using the same Weibull analysis, the durability of the remanufactured part was determined for the same number of years. The durability of the remanufactured products was also analysed on the basis of certain environmental conditions.

Warranty: The main objective of the remanufacturing strategy is to produce as good as new products which have the same competitive market as new products. It should be noted that remanufactured products are required to have the same probability of failure as new products, which means that they will be provided with the same warranty as new products. The warranty calculation for remanufactured products has been determined by following Anityasari (2009).

Carbon footprint and embodied energy consumption

Environmental assessment is an integral part of the technical assessment. Once the technical assessment is completed, the GHG emissions reduction and embodied energy saving associated with the production of remanufactured alternators needs to be assessed.

A streamlined life cycle assessment (SLCA) was conducted to estimate the GHG emissions and embodied energy consumption. It is streamlined because it ignores all downstream activities such as use, disposal and maintenance (Todd and Curran 1999). The SLCA followed the four steps of ISO 14040-44; goal and scope, life cycle inventory, impact assessment and interpretation (ISO 2006).

The goal of the assessment was to calculate the potential global warming impact of the GHG emissions (kg CO_2–eq) and embodied energy (MJ) for a typical remanufactured alternator resulting from the production of alternative materials (kg) and energy consumption (MJ) during remanufacturing operations (Fig. 2).

The goal of this assessment is to assess the global warming impact (kg CO_2–eq) (or Carbon footprint) and embodied energy (MJ) of a typical remanufactured alternator during its life cycle. In the current analysis, the embodied energy includes the energy consumed by processes associated with disassembly, cleaning, inspection, reconditioning, reassembly and testing of a remanufactured alternator.

The scope of this assessment was limited to the factory gate only and packaging was excluded. The system boundary has been developed for this analysis where the boundary includes cores collection, initial inspection and disassembly, cleaning, testing and sorting, reconditioning, reassembly and final testing (Fig. 2).

The life cycle inventory (LCI) is a prerequisite for carrying out an LCA analysis. It includes a listing of the quantitative values of the materials, chemicals and energy used in all stages of the remanufacturing operation from core collection to final testing. Fig. 2 shows the life cycle inventory, consisting of all inputs, processes and outputs (e.g. materials, energy, resources, emissions, and waste) for a 2.2 kg remanufactured alternator.

Once the LCI was developed, the input and output data were entered into Simapro 7.3.3 software (PRe Consultants 2013). The data was linked to relevant libraries or emission databases within the software to estimate GHG emissions. The IPCC global warming potential (GWP) for a 100 y timescale was applied to determine the GHG emissions, and the cumulative energy demand method in the Simapro software was used to calculate the embodied energy (PRe Consultants 2013). Since some Chinese parts were used and the remanufacturing operation was conducted in Indonesia, the Indonesian electricity mix, consisting of lignite (41%), petroleum (29%) and natural gas (17%), and the Chinese electricity mix consisting primarily of hard coal (77%) were considered for electricity generation.

The GWP or carbon footprint is represented as kg or tonne CO_2 equivalent (CO_2 –e) and so all greenhouse gases are converted to CO_2 equivanent GHG emissions following IPCC (2007). Accordingly, carbon footprint (GWP_{co_2-e}) has been calcaulted as follows.

$$GWP_{co_2-e} = \sum_{i=1}^{N}(I_i \text{ x } EF_{iCO_2} + I_i \text{ x } EF_{iCH_4} \text{ x } 25 + I_i \text{ x } EF_{iN_2O} \text{ x } 298) \quad (2)$$

Where,

i :1,2,3,......N, is the input in life cycle inventory

I : amount of input

EF_{iCO_2} : CO_2 emission factor for an imput i

EF_{iCH_4} : CH_4 emission factor for an input i

EF_{iN_2O} :N_2O emission factor for an input i

Following cumulative energy consumption method, the inputs in the life cycle inventory (i.e. Fig. 2) have been multiplied by the corresponding embodied energy consumption values to find out the total embodied energy consumption (EE_{total}) of a remanufactured alternator as shown in Equation 3.

$$EE_{total} = \sum_{i=1}^{N} \mathrm{I}_i \ x \ EE_i \quad (3)$$

Where,

EE_i :Embodied energy consumption of an input i

Determination of threshold values

The threshold values were chosen because they are achievable by remanufacturing SMEs in developing countries while maintaining standard remanufacturing operations. Standard remanufacturing operations are those that use quality cores, a reasonable quantity of used components, and follow all required remanufacturing steps (e.g. disassembly, cleaning and testing) and testing procedures. The remanufacturing operations are conducted by skilled workers. The threshold values for technical and environmental aspects have been chosen from the available values in Table 1.

An optimum value of ≥ 90% for reliability was chosen as it represents the optimum value for the reliability of remanufactured mechanical devices (e.g. compressors, TVs and tires) in Indonesia and can be achieved within the technical and economic constraints of Indonesian remanufacturing SMEs (Ardiansyah 2009). Similarly, the optimum values for durability (two years) and warranty (two years) for remanufactured alternators are applicable to Indonesian remanufacturing industries for maintaining product quality.

The threshold value chosen for energy savings is 75%, as it is the average value for remanufacturing in developing and developed countries while maintaining standard remanufacturing operation. The chosen threshold value for GHG emissions reduction is 77%, as this is the average value from remanufactured products in developing and developed countries where standard remanufacturing practices have been implemented.

Assessment of existing remanufacturing scenario for GHG mitigation

Material reuse and replacement strategies

Both technical and environmental analysis require the information on material reuse and replacement strategies of the existing situation which were obtained by interviewing SMEs in Jakarta and Java of Indonesia in order to develop Table 2. The probability of reuse (i.e. 10 – 90%) is the likelihood that a remanufactured component can be used by remanufacturers at the end of its lifetime. This probability was determined by discussion with the managers of the SMEs in the case study. For example, 60% means that the core component has a 60% probability to being reused in the remanufacturing process. The weight is the proportion of the material (i.e. steel, copper etc.) in the total 2.2 kg weight of the remanufactured alternator. The remanufacturing strategies in Table 2 represent the reusability potential of the components.

If new components are used in the remanufactured alternator, it is necessary to consider all of the upstream emissions and wastes associated with the material and energy consumption of the raw material extraction, production, transportation and foundry processes required to produce these new components. The replacement of an old component with a new component is thus energy and material intensive. The combined weight of a new stator and rotor winding coils, bolts and nuts, brushes, bearings and bearing clamps is about 0.39 kg. In addition, these components are imported from China and Taiwan, meaning that transportation must be included in the analysis to capture the associated environmental impact. The transport of 39.5E-05 t of alternator components from China and Taiwan to Indonesia over a distance of 7,966 km equates to around 1.52 tkm (39.5E-05 t x 7,966 km = 1.52 tkm), which was used for the environmental analysis (Table 2).

The reassembly process is then carried out by assembling the reused, reconditioned and new components into a remanufactured alternator. Following the reassembly process, the remanufactured alternator undergoes final testing, which consists of testing the revolutions per minute (RPM), current output, voltage, cut in speed and noise level to ensure the functionally of the alternator. The testing process is very basic as the case study surveys found that the tester is not able to conduct all of the required testing. For example, in a vehicle, an alternator often operates at high temperatures, the existing testing equipment does not permit the test of reliability and durability of the alternators under such conditions.

Once the final testing has been conducted, a certain warranty period (three months) is offered to the customers to cover the replacement components. The warranty period is the same for private and business purposes, but this is actually not reasonable for business customers who often experience product failure faster than individual customers, as the warranty is not based on the vehicle mileage.

Technical assessment

The technical indicators are reliability, durability, and warranty have been determined prior to GHG emission and embodied energy consumption assessment by using the time series data covering the period from 2008 to 2010 which was collected from the SMEs involved in this study.

Reliability: The alternator reliability analysis was conducted by using information on the number of products sold (8,490 alternators), the number of failed alternators (3,838), the number of suspended products (4,652 alternators), the time to failure of the products (230 d), and the suspension time of products (360 d) from the SMEs in this case study.

Since cars are not used for the whole day, the average number of daily driving hours for Indonesian people (6 h) was used to determine the time to failure (TTF) value of the alternator. This value was obtained through interviews with randomly selected motorists in Java. The TTF data was then analysed using Reliasoft ++ software version 8 (Reliasoft 2013). Once all the data had been entered into the software, the reliability of the remanufactured alternator was analysed using the Weibull distribution. The reliability analysis was calculated using the maximum likelihood estimation (MLE), Fisher Matrix and median rank methods. The results obtained from the Weibull distribution showed that the shape parameters (β), which were failure mode, were around 2.4, while the scale parameters (α), which were alternator life, were about 1,288 d. The Weibull reliability plot displaying the relationship between reliability and the time for remanufactured alternators is presented in Fig. 3.

Following Eq. 1, the mean time to failure for the remanufactured alternators was estimated to be 1,142 d. The reliability of the remanufactured alternators was compared with the threshold value of ≥ 90%. This level of reliability was regarded as the minimum standard for manufacturing products which could be achieved by the remanufactured alternators (Anityasari 2009). However, the reliability of the remanufactured alternators produced by these SMEs (78% in two years) was even lower than the lower limit (90%) of the threshold value.

Durability: The durability analysis includes the estimation of the failure free life period of the remanufactured alternators. This period is estimated to be 12 months, during which the remanufactured alternator is expected to run for 19,000 km under typical Indonesian vehicle operating conditions (i.e. hot temperature of 105 °C, speeds of 1,800 RPM, sound level of 85 decibels and vibrations of 1.2 A).

According to the existing scenario, no proper durability testing has been conducted by these SMEs. The current alternator testing procedure is only performed at very a basic level including testing speed, sound level and vibrations using conventional equipment (i.e. multimeter, sound level meter), as mentioned earlier.

The Weibull analysis which was used to determine the reliability of the remanufactured alternators was also utilized to determine the durability. The results showed that the durability of the remanufactured alternators was only 78% over two year, far less than the lower limit of the threshold value (≥ 90%) (Anityasari 2009). The lower limit of the threshold value was determined on the basis of the durability of an alternator under high temperatures, speeds, sound level and vibrations (Jung et al. 2008, Woo et al. 2008).

Warranty: Warranty has become an important part of consumer and commercial transactions, particularly in the remanufacturing industry. This is because it helps to provide protection for both producers and consumers in terms of product quality guarantee and sales improvement. According to the results of the reliability analysis, if 1% of the components failed during the warranty period, the remanufactured alternator could survive at least six months in order to achieve 99% reliability.

As it is assumed that a vehicle will be used for an average for six hours a day, the six months would be equal to 1,080 h of use (three years). Accordingly, the SMEs could have offered a maximum warranty of three years which is more than the warranty periods currently offered in the market (i.e. two years). However, in a real-market situation, the SMEs provide only three months warranty, which has resulted in a 20% fall in remanufactured alternator sales on the market. Reasonable costs to honour the warranty are required in order to survive in a competitive market.

Since the technical criterion are not met, no further analysis for estimating GHG emissions saving considered. The technical, performance of the existing scenario was not sustainable due to the high number of failed components, large proportion of poor quality used parts, absence of modern testing facilities, and lack of skilled workers. As a result, a number of possible improvement scenarios involving new remanufacturing strategies for Indonesian SMEs have been developed to find technically feasible remanufactured alternators for estimating GHG mitigation potential .

Improvement scenario I

Remanufacturing strategy

A failure analysis conducted in the current study considered all of the failure data collected during three consecutive years (2008 – 2010). The results showed that the majority of failure was caused by the regulator (64%) followed by the rectifier (13%), brush (12%) and other components (11%), such as the stator and rotor. One prominent way of making a very high quality remanufactured alternator could be by replacing most of the old components with new ones except for the housing, and the stator and rotor casings which are reconditioned and do not affect the quality and performance of the remanufactured alternator. Based on this strategy, improvement scenario I considered replacement of all critical components with new ones. The old critical components and materials included the regulator, rectifier, brush and other worn components including the coil winding stator and rotor, pulley, insulation, bolt and nut, bearings and clamps, which were to be replaced with new ones that were usually imported from China and Taiwan.

The Integrated Circuits regulator, rectifier and brush contributed the most (84%) to the failure of the remanufactured alternators. Replacing them with new ones was expected to reduce the chance of failure of the remanufactured alternator. Other small components including the insulator, pulley, bolt and nut, bearing and bearing clamps were also considered for replacement, as the field survey showed it was cheaper to buy new parts than to recondition the used ones. Due to poor core quality, the burnt out rotor and stator were also to be replaced with new ones in this scenario.

Technical analysis

Reliability: A reliability parameter was allocated to all new components replacing existing parts and materials (i.e. regulator, rectifier, brush, slip rings, stator winding, rotor winding, bearing and pulley). Other components, including the bosh holder, insulator, rotor shaft, finger poles, laminated iron frame, stator lead and neural junction, front case, back case and fan bolt and nuts were found not to have failed and the reliability of these components was thus determined using exponential distribution. Some raw data such as the type of product, component specification, date of purchase, sales data, failure date, number of failures, type of failure and number of suspensions were gathered from the SMEs to determine the values for suspension and failure of remanufactured products. An investigator triangulation method has been carried out to determine the failure rates of the components of this remanufacturing strategy (Dyker et al. 2006). Accordinly, the failure rate of these components (0.1%) was discerned by consulting with the surveyed SMEs using a structured questionnaire which was cross-checked with the Military Standardization and Reliability Handbooks.(Weibull Com 2014).

The reliability analysis was then conducted by applying series and parallel relationships between the components of the remanufactured alternator to estimate the reliability of the remanufactured alternator for improvement scenario I as shown in Fig. 4. The steps followed to discern the reliability by using the series-parallel relationship between component reliabilities are as follows:

- Firstly, reliability values for all series connections including the rotor assembly, stator assembly and carbon brush assembly were determined.
- Secondly, following Fig. 4, the reliability value for the parallel connections was determined.

The reliability of the remanufactured alternator in improvement scenario I (97.9%) is not only higher than it is in the existing scenario (78% over two years), but is also much higher than the lowest limit of the threshold value (≥ 90%). This increased reliability is due to the replacement of old components with new ones. However, this could increase the life cycle cost of the remanufactured alternator and the environmental impact resulting from the mining and manufacturing processes associated with the production of the new components (Biswas and Rosano 2011).

Durability: The durability of the remanufactured alternator in improvement scenario I was estimated to be 97.9% due to the increase in reliability to 97.9% over two years. In order to ensure a durability higher than that in the existing scenario, a durability testing framework that allows to measure the durability of the alternator at high temperature (i.e. 105°C) for a period of 20 s. An efficiency of 90% or more has to be achieved for a standard durability testing. Otherwise, the remanufactured alternator needs to be rechecked and then retested to meet the durability requirement which is at least the lower limit of the threshold value for durability (≥ 90%). It is recommended that Javanese SMEs adopt these advanced alternator testers in order to maintain a technical performance that will provide customer satisfactions.

Warranty: The reliability value and the mean time to failure (MTTF) of the remanufactured alternator were then used to determine the warranty period for the remanufactured alternator. Some information including the warranty period of the new alternator (two years), a nominal customer risk (NCR) (0.0361) of two years, average life of a new alternator (4 y), and the reliability of the remanufactured alternator (97.9%) were used to estimate the warranty period and the end of life estimation of the remanufactured alternator for improvement scenario I. The warranty period of the remanufactured alternator under this scenario was estimated to be two years with a life expectancy of about four years, which is very high compared to the existing scenario.

Summary: Interestingly, all technical criteria including reliability, durability, and warranty met the threshold values, which was due to the increase in the use of new materials, introduction of new testing technology and the expansion of the collection area. Once the technical criterions are met, the next step is to discern as to whether required level of GHG emissions can be mitigated so that threshold values are met.

Environmental impact analysis

Embodied energy saving: Following the same approach (cumulative energy demand method) as for the existing scenario, the embodied energy of the remanufactured alternator in improvement scenario I was estimated to be 116 MJ. This embodied energy value is much higher than the threshold value or that of the existing scenario due to the use of a large portion (68.7%) of virgin materials as shown in Fig. 5. Specifically, the use of energy intensive materials including copper (17.1%), cast iron (9.8%) and steel (9.1%) increased the embodied energy consumption significantly. The use of any new components takes into account all energy consumption in the mining, processing, transportation and manufacturing .stages of new components, thus increasing the amount of embodied energy in improvement scenario I. Therefore, the embodied energy saving benefits were only 56.2% (or (148.9-116)*100/148.9) of the total embodied energy (148.9 MJ) for a new alternator. This value is less than the threshold value which is about 75% of the total embodied energy of a new alternator.

GHG emissions: The Intergovernmental Panel on Climate Change (IPCC) 2007 global warming potential which was used in the existing scenario, has also been employed in improvement scenario I to determine the GHG emissions for a remanufactured alternator. The GHG emissions from the remanufacturing of an alternator in improvement scenario I were estimated to be about 6.4 kg CO_2–eq. The GHG saving associated with the replacement of new alternators with remanufactured ones was estimated to be 10.1 kg CO_2–eq (61.5%) per remanufactured alternator. This percentage (61.5%) of GHG saving is far less than in the existing scenario (75%) and the threshold value (77%).

Like the embodied energy hotspot, the GHG emissions associated with the replacement of old materials with new materials also contributed to a significant portion (71.4%) of the GHG emissions in this scenario (Table 3). Thus, as discussed in the previous energy analysis, the composition of recycled materials, and reused and new components, needs to be determined in a way that will reduce both GHG emissions and embodied energy consumption while meeting the requirement for technical viability. As stated earlier, the mining, processing and manufacturing processes in the upstream activities for new component production have added a significant quantity of GHG emissions to the life cycle of a remanufactured alternator.

Summary : Although the technical criteria were met, improvement scenario I did not achieve the threshold values for embodied energy consumption, and GHG emissions. The main reason for not meeting the threshold values is the increased quantity of virgin materials, and the reduction in used components and materials, as well as the increase in transportation needed for importing new components.

Improvement scenario II

Remanufacturing strategy

Improvement scenario II, which involves the use of both recycled and used material, was considered for the technical and environmental analysis in order to overcome the problems in Scenario II.

It is proposed that the old material and components in the existing scenario, including rotor and stator winding copper, be replaced with recycled material for the following reasons: From the technical and economic points of view, recycled copper has been found to have the same quality (i.e. reliability, durability) as virgin copper and it is cheaper and readily available on the market (Copper Recycling and Sustainability 2014)

From an environmental point of view, the replacement of new copper with the recycled copper could save up to 90 % of embodied energy (Fatimah 2014).

Other alternator components including the housing, laminated iron stator, rotor shaft, slip ring, fan, bolt and nut and pulley were reconditioned for reuse in this scenario. These reconditioned parts were found not to have failed and they are found reusable at the end of the alternator life (SAE International 2001).

It was proposed that critical components including the regulator, rectifier, brush and bearing be replaced with new ones, since these components have been found to contribute to the failure of remanufactured alternators in the existing scenario. In addition, it is cheaper to buy new regulator, rectifier and brush than to spend money on reconditioning old components. The bearing has never been found to be suitable for either repairing or remanufacturing (Biswas and Rosano 2011).

Therefore, in addition to 1.15kg (57%) of reused parts in the existing scenario (Table 1), 0.11kg equivalent weight of beering and bolts (i.e. 5% of the total weight) It was estimated that approximately 62.2% of the materials and components were reused (or 63% of the total weight of a 2.2 kg alrenator), and the rest were intended to be replaced with recycled materials (15%), old materials (3%), and new materials (13%). The main difference between improvement scenario I and improvement scenario II is that recycled copper is used instead of new copper.

The use of recycled, old and reused materials in remanufactured alternators has reduced the use of new materials to 13% (0.29 kg), which is expected to improve environmental performance by reducing upstream GHG emissions and embodied energy consumption. The following technical assessment will show whether the reduction in use of new materials affects the quality of the remanufactured alternators.

Technical analysis

Reliability: Firstly, the reliability of all of the components of the remanufactured alternator was determined. The reliability of the recycled materials was considered to be the same as the new components (100%), which implies that the failure rate of the new components has been assigned zero. The reused components, including front case, rear case, slip rings, fan, bosh holder, insulator, rotor shaft, finger poles, laminated frame, stator lead and neural junction, were not found to demonstrate any failure in the existing scenario.

The reliability of the remanufactured alternator was calculated by integrating the overall reliability of the components. The reliability calculation was performed for the overall reliability of components connected through series and parallel connections. The series system included the rotor assembly, stator assembly, diode rectifier, regulator and carbon brush while the parallel system included the rest of the components (i.e. rear case, fan, pulley, pulley clamp, bolt and nut).

Following the above approach, the reliability of the remanufactured alternator improvement scenario II was estimated to be 95.8%. Even though the reliability of remanufactured alternators in this improvement scenario is lower than in improvement scenario I, this scenario has met the threshold values.

Durability: The durability of remanufactured alternators has been estimated to be 95.8% which is higher than for the existing scenario due to the increase in reliability (95.8%) of the remanufactured alternators in improvement scenario II. The use of recycled copper does not affect the reliability and durability of alternators as confirmed by Copper Recycling and Sustainability (2014). .

Warranty: The warranty analysis of the remanufactured alternator was conducted by using the reliability value of 95.8%. The warranty period was estimated to be at least two years while the end of life of the remanufactured alternator was estimated to be four years. The warranty period therefore meets the threshold value of two years.

Summary: Since all technical criterion are met, GHG emissions and embodied energy consumption analysis have been conducted and then have compared with the threshold values.

Environmental impact analysis

Embodied energy: The total embodied energy for remanufacturing an alternator in improvement scenario II was estimated to be 93.8 MJ. The use of recycled materials and used components significantly reduced the total energy consumption of alternator production from 116 MJ (44%) in improvement scenario I to 93.8 MJ (35%) in improvement scenario II. This is mainly because of the use of recycled copper in the rewinding process as the recycling of copper requires 90% less energy than making new copper.

The total embodied energy for remanufacturing an alternator has been compared with that for the manufacturing of a new one to determine the potential energy recovery of this improvement. The results showed that the remanufacturing of alternators using improvement scenario II could conserve a significant amount of energy (65%) compared to improvement scenario I, but that the scenario does not yet meet the threshold values.

The replacement of new material with recycled material was initially expected to save a significant amount of energy (20%) in comparison with the replacement of old materials with new.

GHG emissions: The GHG emissions of 2.2 kg for the remanufacture of alternators in improvement scenario II were estimated to be 5.1 kg CO_2–eq. The replacement of a new alternator with a remanufactured alternator using improvement scenario II could reduce GHG emissions by 69%.

This reduction is mainly because the percentage of new components has been reduced from 43% in improvement scenario I to 13% in improvement scenario II, thereby reducing the upstream GHG emissions from the mining, processing and manufacturing of virgin materials for new components. Whilst the use of new components decreased significantly by 30%, the replacement of old materials with new materials is still a GHG hotspots (65.1%) in this scenario due to the use of recycled materials

Further investigation shows that the cast iron foundry for rectifier production would consume a significant amount of energy (8.23 MJ), which could be reduced by using used rectifiers. To facilitate this, it is important that high quality used rectifiers be used. Furthermore, to maintain the rectifier quality, the part should be tested using a standard procedure to achieve the best performance.

Summary : Whilst technical criteria were met, improvement scenario II was not found to meet the threshold values for major environmental impacts criteria, including material and energy consumption and GHG emissions, due to the use of a large quantity of recycled materials that were energy and carbon intensive. The following remanufacturing strategy will use a different composition of used, recycled and new materials in order to address both technical and environmental viabilities.

Improvement scenario III

Remanufacturing strategy

On the basis of the technical and environmental analysis of Scenario II, the factors which have been recognized as obstacles to achieving sustainable manufacturing are as follows.

The use of recycled copper in rotor and stator winding still contributed to a significant portion of the total GHG emissions and embodied energy due to the recycling process involving collection, cleaning, melting, and manufacturing.

The use of new materials including bearings, regulators, brushes and rectifiers still contributed to high embodied energy consumption and GHG emissions due to the manufacturing process (i.e. refining, manufacturing, casting, machining) and transportation activities.

In improvement scenario III, the reuse option has been considered where both stator and rotor were reused to improve the environmental performance of alternator remanufacture. Once the stator and rotor were fitted, they were balanced and then varnished. Fig. 6 shows the breakdown proportions of used, recycled, new and old parts of a remanufactured alternator for existing and improvement scenarios I, II and III.

Since critical components including the bearing, regulator, rectifier and brush that account for 13% of the total weight of the alternator cause the majority of failure, they are required to be replaced with new parts. In addition, the use of a new bearing is an economically viable option for increasing reliability because it is cheaper to buy than to recondition. The bearing is a sensitive component as its failure could lead to the breaking down and failure of the entire alternator.

The remaining used components including the housing (front and rear case), fan, slip ring and pulley were reconditioned by painting the housing, using a grinding machine to remove abrasions on the fan, and a lathe for turning the rough slip ring. The quantity of used parts was increased from 62% in improvement scenario II to 87% in improvement scenario III.

Technical analysis

Reliability: The reliability of new components including the IC regulator, rectifier, bearing and brush were considered the same as for improvement scenario II (100%). The reliability of the pulley, holder, bosh holder, insulator, bolt and nut and bearing clamps were determined by consulting with the SMEs (and these reliability values were checked with the standardization book and literature (Weibull Com 2014).

Using the reliabilities for all of the individual components, the reliability of the remanufactured alternator was estimated to be about 95.6%. This was higher than the threshold value, which means that the proposed modification will not affect the performance of the alternator. The majority (87%) of the components were reused. The critical components, which make up 13% of the total weight of the alternator, have relatively higher failure rates (i.e. 65% for the IC regulator, 13% for the rectifier, 12% for the brush) and have been replaced with new ones to maintain the required reliability of the remanufactured alternator.

In addition, the majority of the reusable components are not expected to exhibit failure as they have undergone proper reconditioning and machining processes and higher quality cores have been considered for use. These factors will increase the reliability (Gray and Charter 2007). In addition, more accurate initial testing was considered to ensure the reduction of the failure rate and to maintain the reliability and durability of the remanufactured alternators.

The reliability of improvement scenario III was found to be higher than that of the existing scenario and the threshold value. This means that the increased use of reused components, advanced testing methods and the use of quality cores could maintain the technical performance of the remanufactured alternator at threshold value level.

Durability : The higher reliability of the components which ranged between 97% and 100% in improvement scenario III was expected to increase the durability of the remanufactured alternator (i.e. 95.87%). Therefore, the same durability tests used for improvement scenarios I and II (i.e. high temperature, high speed and vibration) were conducted for improvement scenario III, and it was found that the durability standard (90% or more) was maintained.

Warranty: Since the reliability of the remanufactured alternator under improvement scenario III is almost the same as that under improvement scenario II (95.6%), the warranty period for improvement scenario III remained unchanged (2 y). The same life time of four years for the remanufactured alternators was considered for both scenarios.

The analysis of the warranty period for improvement scenario III produced the same result as for improvement scenario I and improvement scenario II, where the increase in reliability provided a greater opportunity for SMEs to offer a longer warranty period (2 y). However, the economic challenges which are often experienced by SMEs due to financial limitations need to be addressed in order to provide suitable warranty costs and optimal warranty protection. Moreover, an additional warranty period could be an attractive option for customers who want greater reliability.

Environmental impact analysis

An environmental impacts analysis was conducted for improvement scenario III as follows.

Embodied energy saving: The total embodied energy in improvement scenario III was estimated to be about 65.5 MJ . The remanufacturing process in improvement scenario III only consumed about 24.7% of the total embodied energy required for manufacturing new alternators (265 MJ). About 75.3% (199.5 MJ) in embodied energy consumption can be saved by replacing a new alternator with a remanufactured one. Table 4 that improvement scenario III was not only able to save more energy than the other scenarios, but also met the threshold values.

A significant energy saving is possible due to avoiding the energy consumption in upstream activities, including mining, processing and manufacturing associated with the production of new material, as well as by avoiding the recycling process.

GHG emissions: The carbon footprint of the remanufactured improvement scenario III was estimated to be 3.59 kg CO_2–eq, which is 21.8% of the total GHG emissions for a new alternator (16.5kg CO_2–eq). It was found that the remanufacturing process in improvement scenario III could offer significant GHG savings (78%) compared to the other scenarios, and it also supersedes the threshold value (77%).

The GHG emissions in improvement scenario III mainly result from replacement with new components (54%) followed by reconditioning (20%) and cleaning and washing (14%). The GHG emissions for new components including the bearing (9.2%), IC regulator (40%), rectifier (46%) and brush (5%) are presented in Table 5.

Table 5 shows that the rectifier contributed the largest quantity of GHG emissions as it is made of a number of virgin materials including aluminium, copper, cast iron and plastic, thus adding the energy consumption in the supply chains of mining, manufacturing and transportation of materials. As the rectifier has been found to be the hot spot component, the technical feasibility of the reuse of this component needs to be assessed in order to reduce the embodied energy.

GHG emission mitigation through remanufacturing at national level

Fatimah (2014) estimated that about 5.6 million alternators could be sold on the Indonesian market per year. According to interviews with a number of auto parts shops, reused and remanufactured alternators contribute about 10% of the total number of alternators on the market (0.56 million alternators). The GHG mitigation associated with the replacement of 0.56 million new alternators with remanufactured alternators produced under the improvement scenario III would be 7.2 kt and the embodied energy consumption saving would be 111.7 TJ. This total amount of GHG emissions avoided is roughly equivalent to taking 360 small cars off the road over a period of 5 y (Biswas, 2013).

Given that there are opportunities to increase the market share of remanufactured products, Table 6 shows that there would be an increase in sales and GHG and embodied energy saving benefits associated with an increase in market coverage for the remanufactured alternators. It can therefore be derived from these information that the increase in market share to 40% for remanufactured alternators is equivalent to taking 1,440 small cars off the road for 5 y.

In the case of Indonesia, where the SMEs significantly dominate Indonesian industry (99.99%) (Tambunan 2006) and the manufacturing is considered as one of the main economic supports of SMEs, remanufacturing has a tremendous potential for GHG mitigation. This paper has dealt only with the case of remanufactured alternators, but there are remanufacturing opportunities in Indonesia for other common items including computers, agricultural machinery and white goods not only for environmental reasons but also for affordability concerns. For example, Fatimah and Biswas (2015) found that the introduction of technically feasible remanufactured computers can mitigate significantly higher GHG emissions than the remanufactured alternators (13 kg CO_2–eq saving potential for a remanufactured alternator VS 2 t CO_2–eq for a remanufactured computer) although the number of sales for former may not be same as the latter.

Conclusions

This paper has demonstrated that remanufacturing operation has a significant potential in least developed Asian countries to address climate change by reducing GHG emissions. Since remanufactured products are yet to gain popularity in developing countries due to quality issues, this paper has endeavored to carry out technical analysis by identifying remanufacturing strategies offering required level of reliability, durability and warranty period. The existing remanufactured alternators in Indonesia were not found technically feasible and therefore, a number of improvement scenarios were considered to attain environmentally feasible solutions.

In remanufacturing strategy I, the quantity of new materials was increased in order to decrease the quantity of poor quality used parts in the production of remanufactured alternators. This strategy was found to be technically viable but not environmentally feasible. The second remanufacturing strategy decreased the quantity of new materials and increased the proportion of recycled materials. Again, the strategy was not found to satisfy with all environmental criteria. Hence, remanufacturing strategy III employed a greater quantity of high quality used materials which proved to be a technically feasible and environmentally friendly solution.

If the third remanufacturing strategy is applied to all existing SMEs in Indonesia remanufacturing alternators, an equivalent amount of GHG emissions that could emit from 360 small cars over 5 y can be avoided. Therefore, it is important for Indonesian Government to provide financial incentives in terms of canon credits, soft loan, training facilities and logistics to popularize remanufacturing in SMEs and to produce exportable items by enhancing local economy.

The Indonesian Program for Pollution Control Evaluation and Rating, PROPER, which has developed pollution databases could potentially be benefitted from this research Nyiwul et al. 2015). .A further study needs to be carried out to assess economic feasibility of remanufacturing activities in order to achieve low carbon economy in Asia.

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Table 1 Available indicator values for technical aspects

Indicators	Available values		Description
	Value	Sources of information	
Reliability	≥ 90%	(Anityasari 2009)	This represents the optimum value for the reliability of remanufactured mechanical devices (e.g. compressors, TVs and tires) in Indonesia.
	100%	(Andrew et al. 2006, Steinhilper and Brent 2003)	This represents the reliability of remanufactured products which are considered as good as new in developed countries.
Durability	≥ 90% over two years	(Anityasari 2009)	This represents the optimum value for the durability of remanufactured mechanical devices (e.g. compressor) for the local situation.
	Three years	(Nasr 2012, Remy International 2014)	The durability of remanufactured products is considered to be the same as for new products (i.e. three years) mainly from developed countries' perspective.
Warranty	Two years	(BBB Industries 2014, Kim et al. 2008)	This represents the optimum warranty value for remanufactured products in the Indonesian market. This warranty is applied to the majority of the remanufactured products in developed countries.
Energy savings	78–89%,	(Liu et al. 2005)	This represents the energy savings for remanufactured alternators and auto parts in China.
	68–83%	(Smith and Keoleian 2004)	This represents the energy savings due to the use of remanufactured engines in USA.
GHG emissions reduction	88%	(Liu et al. 2005)	This value represents the optimum GHG emissions of remanufactured auto parts (i.e. engines) in China.
	73%–87%	(Smith and Keoleian 2004, Kim et al. 2008)	These values represent the GHG emissions savings for remanufactured engines and alternators in developed countries (e.g. the US, Germany).

Table 2 The material sources, weights and probabilities of reuse of remanufactured alternator components.

Part	Material	Weight (% of total weight)	Unit	Probability of reuse (%) (a)	Remanufacturing strategy (b)
Housing	Aluminium	570 (26)	g	80	R
Stator	Steel	450 (20.5)	g	90	R
	Lead	10 (0.5)	g	50	R
	Plastic	2 (0.1)	g	20	RwN
	Copper winding	200 (9)	g	20	RwN
Rotor	Cast iron	70 (3)	g	60	R
	Steel	50 (2.3)	g	60	R
	Plastic	2 (0.1)	g	20	RwN
	Copper winding	120 (5.5)	g	20	RwN
Fans	Aluminium	30 (1.4)	g	60	R
Slip ring	Copper	20 (0.9)	g	60	R
Pulley holder	Steel	30 (1.4)	g	60	R
Bosh holder	Steel	25 (1.1)	g	80	R
IC regulator	Plastic	5 (0.2)	g	60	RwU
	Copper	5 (0.2)	g	60	RwU
	Cast iron	5 (0.2)	g	60	RwU
	Aluminium	50 (2.3)	g	60	RwU
Pulley	Steel	150 (6.8)	g	80	RwU
Rectifier	Cast iron	100 (4.5)	g	60	RwU
	Copper	50 (2.3)	g	60	RwU
	Plastic	20 (0.9)	g	60	RwU
Insulator	Plastic	65 (3)	g	60	RwU
Bolt and nut	Cast iron	90 (4.1)	g	70	RwN
Brush	Carbon	5 (0.2)	g	10	RwN
Bearings	Steel	50 (2.3)	g	20	RwN
Bearing clamps	Cast iron	20 (0.9)	g	40	RwN

R = reused (existing component is reused), RwN = replaced with new (the replacement of old components with new components), RwU = replaced with used (the replacement of component with other alternator components). RwR = replaced with recycled (represents the replacement of old component with recycled material).

Table 3 The breakdown of GHG emissions in terms of inputs in improvement scenario I

Process	GHG emissions (%)	Process	GHG emissions (%)
Product recovery	3.8	Reconditioning	13
Disassembly	1.4	Replacement	71.4
Inspection	0.7	Reassembly	0.4
Washing & cleaning	7.8	Final testing	0.7

Table 4 Comparison of energy savings between different scenarios

	Existing scenario	Improvement scenario I	Improvement scenario II	Improvement scenario III	Threshold values
New component replacement (%)	22.3	42.8	22.3	13	19
Energy consumption (MJ)	76.5	199.5	93.8	65.5	66.3
Energy saving (%)	71.1	56.2	64.6	75.3	75

Table 5 The breakdown GHG emissions in terms of stages of the critical components in Improvement scenario III

Component	Material	GHG emissions (kg CO2–eq)		
		Mining	Manufacturing	Transportation
IC regulator	Aluminium, copper, cast iron, plastic	0.64	0.13	0.10
Rectifier	Cast iron, copper, plastic	0.35	0.39	0.26
Bearing	Steel	0.07	0.12	0.01
Brush	Carbon	0.01	0.02	0.08

Table 6: GHG and embodied energy saving at national level

Market share (%)	Number of sales (units)	Embodied energy saving (GJ)	GHG saving (tonnes of CO_2–eq)
10% market coverage	560,000	1,11,720	7,207.2
20% market coverage	1,120,000	2,23,440	14,414.4
30% market coverage	1,680,000	3,35,160	21,621.6
40% market coverage	2,240,000	4.46,880	28,828.8

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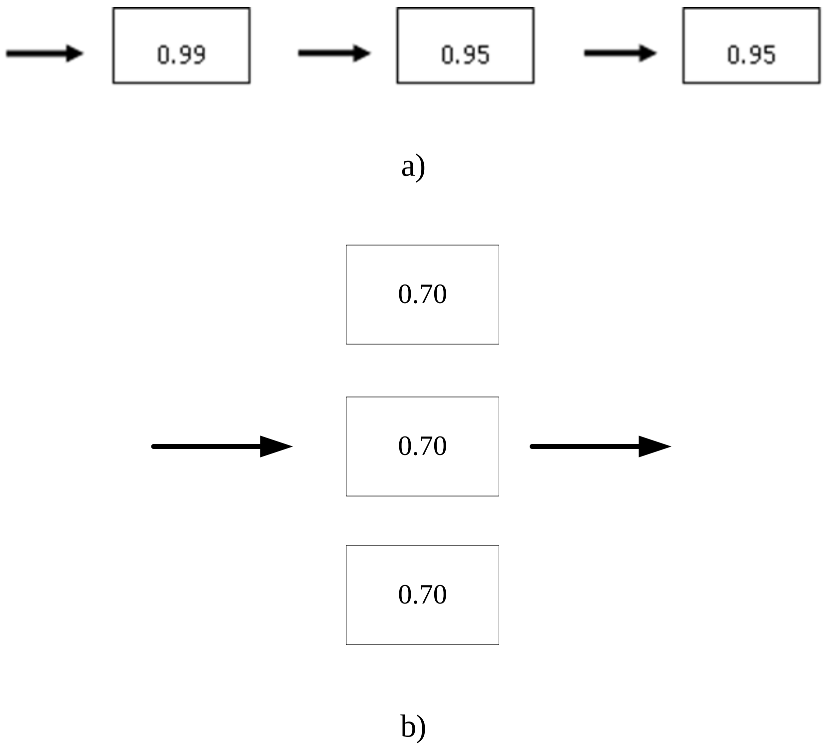
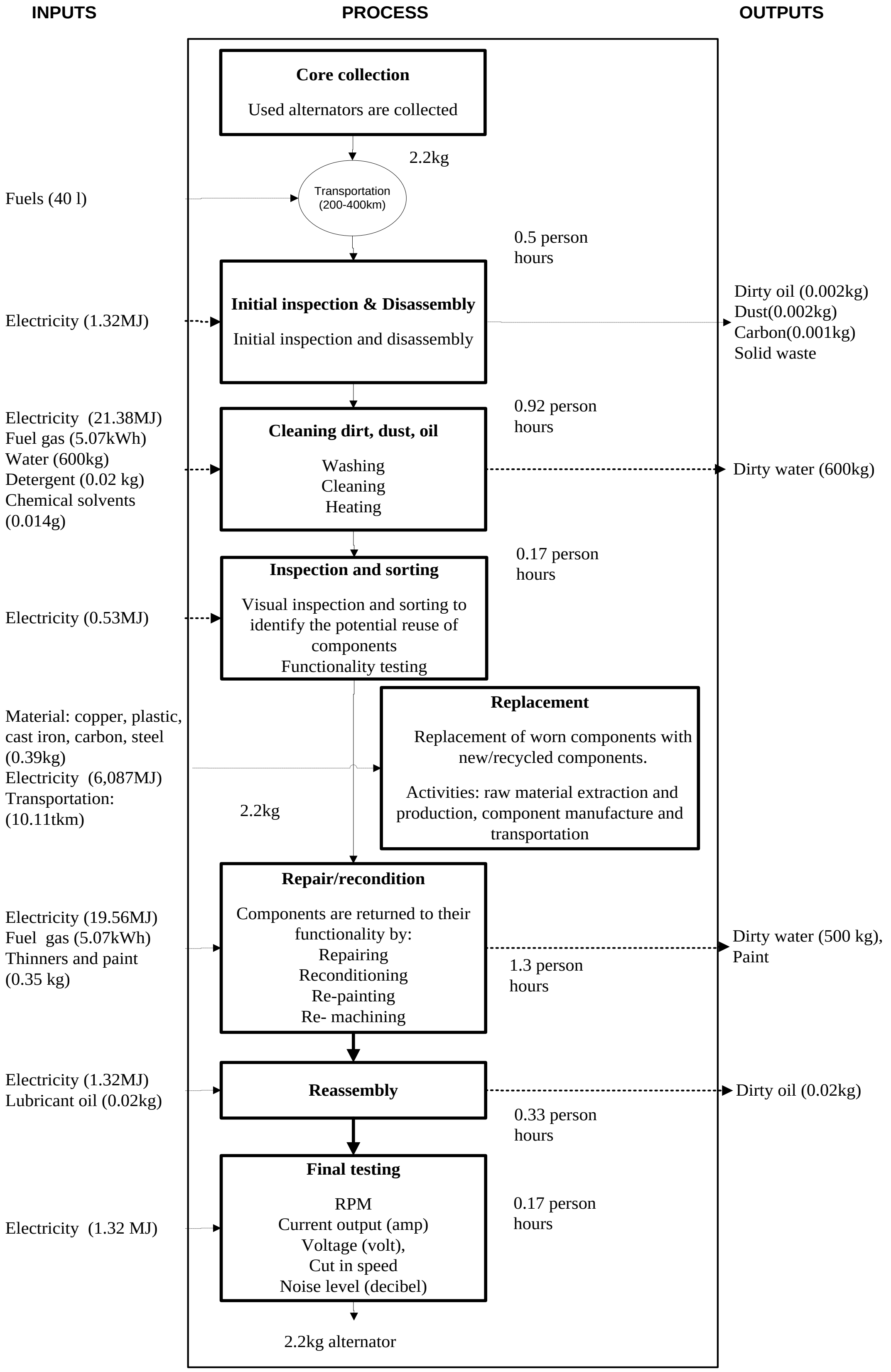


Fig. 1 Examples of series (a) and parallel (b) systems



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893 **Fig. 2** The life cycle inventory of a remanufactured alternator

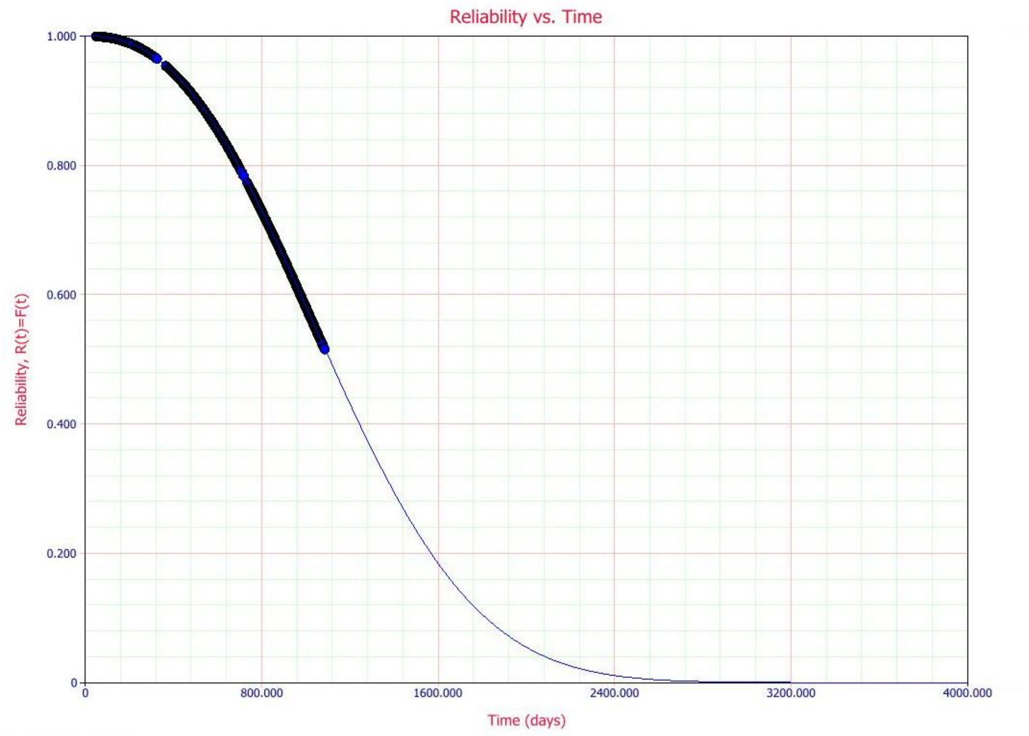

Fig. 3 The Weibull reliability plots for remanufactured alternators

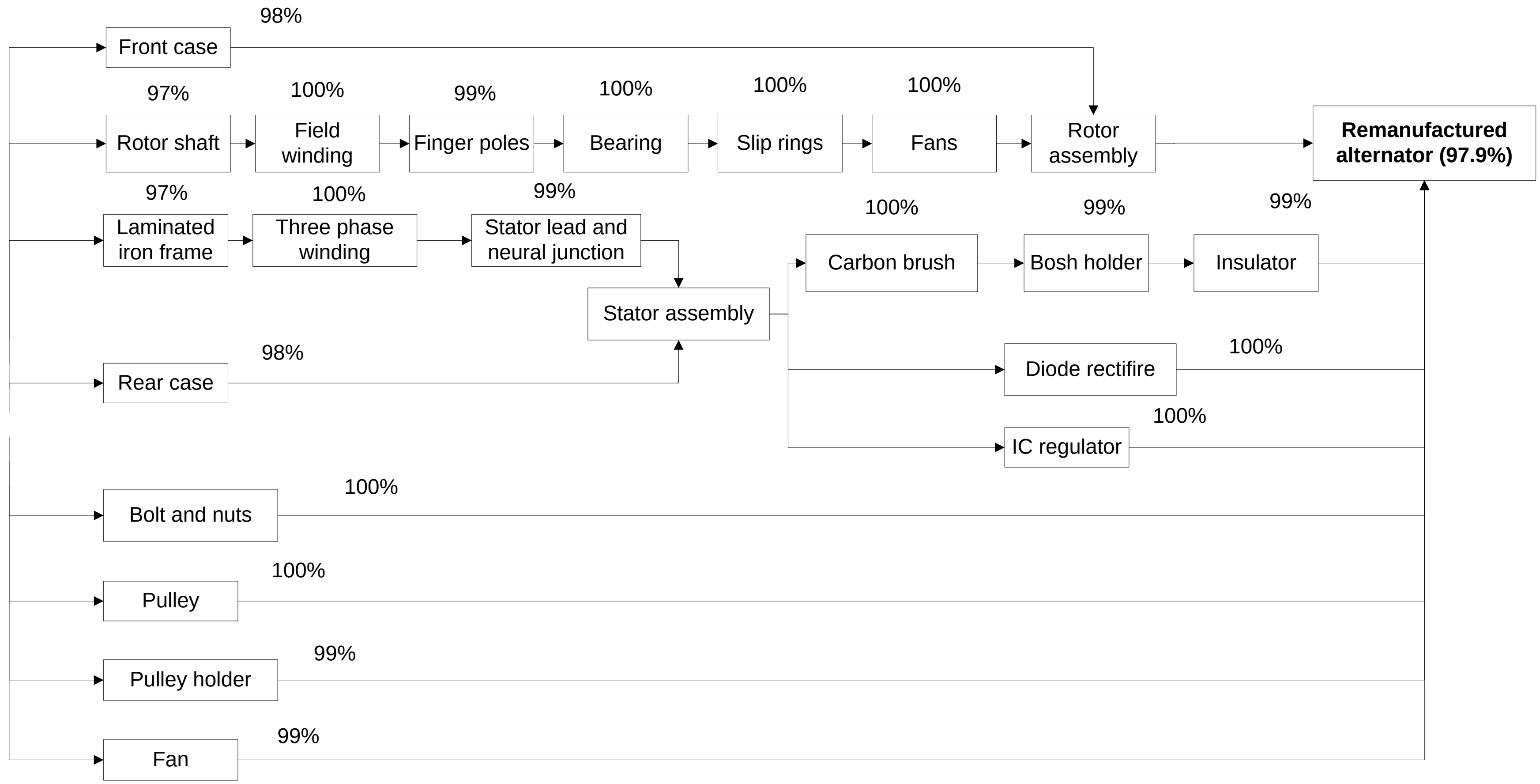

Fig. 4 Series and parallel relationships between the components of the remanufactured alternator for Improvement Scenario I (43% new components, 57 % used components)

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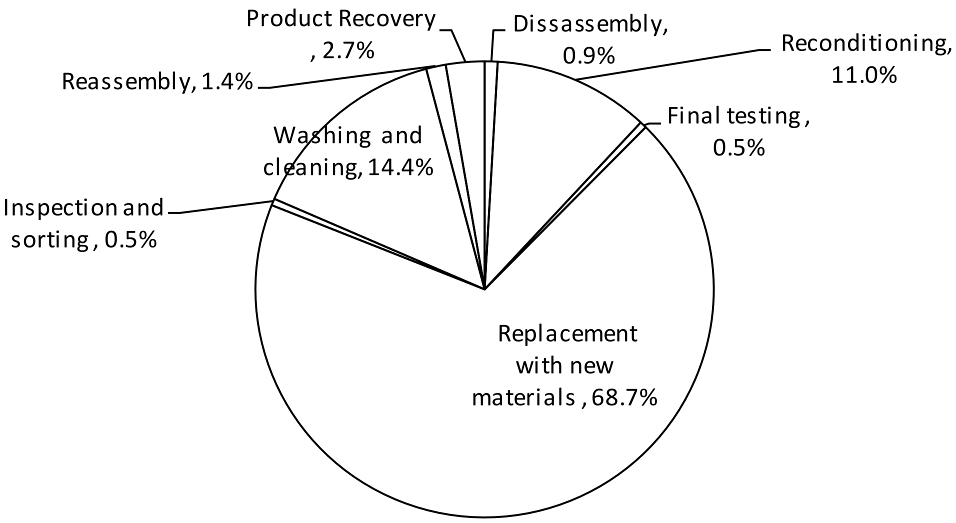

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906 **Fig. 5** The breakdown of embodied energy in improvement scenario I

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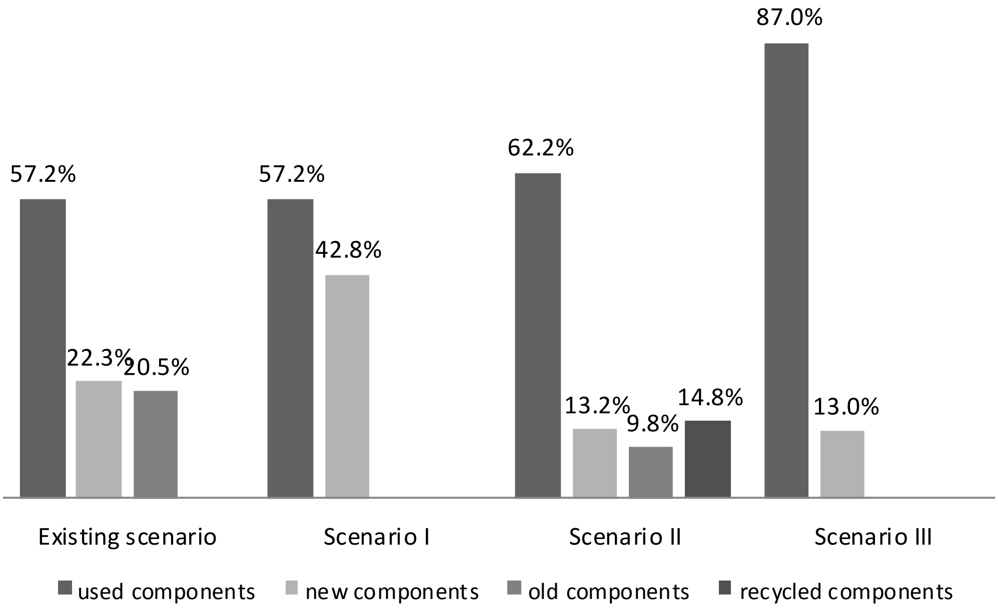

Fig. 6 The breakdown proportions of used, recycled, new and old parts of a remanufactured alternator for existing and improvement scenarios I, II and III