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The advantages of remanufacturing from the perspective of eco-efficiency analysis: A case study

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Abstract

This paper presents a comparison of the eco-efficiency of a newly manufactured cylinder block and the eco-efficiency of a remanufactured cylinder block. For the environmental dimension, global warming potentials (GWP) of the cylinder blocks are considered and measured using life cycle assessment (LCA) methodology. For the economic perspective, the prices of the cylinder blocks are taken into account. The eco-efficiency portfolio of the cylinder blocks is constructed through a series of normalization processes. It is found that the remanufactured cylinder block results in a 90% reduction in GWP and a 39% reduction in cost. The value of the GWP to cost relation (*R*-value) of the cylinder blocks is 0.44 and indicates that cost is more important than GWP by about a factor of 2. Furthermore, the eco-efficiency portfolio shows that the remanufactured cylinder block has a better eco-efficiency by about 62%, if compared to the eco-efficiency of the newly manufactured cylinder block. This study supports the claim stating that remanufacturing is a better end-of-life option in reducing the environmental and economic impacts of products.

Keywords: cost; eco-efficiency; global warming; manufacturing; remanufacturing

1. Introduction

Human activities have a major contribution to greenhouse gases emission. US EPA [1] reported that industrial sector has contributed around 19% to the global level of greenhouse gases emission. According to Afrinaldi et al. [2], among the sector of industry, automotive industry has received more attention.

Using life cycle assessment (LCA) methodology, Li et al. [3] showed that diesel engine manufacturing has a contribution of 51% to the global warming potential (GWP) of the pre-consumer stages (mining, raw materials production, and engine manufacturing) of the life cycle of the engine. Jiang et al. [4] used input-output life cycle assessment (I/O LCA) to measure the environmental impact of diesel engine manufacturing process. Similar to [3], Jiang et al. found that, among the pre-consumer stages, the manufacturing process accounts for around 44% of total CO_2 emission.

To reduce and ease the environmental impact of the manufacturing process of automotive products, remanufacturing is regarded as one of the best solutions. Remanufacturing is a series of processes, involving disassembly, cleaning, inspection, and repair, aiming to restore the functionality of products that have reached their end-of-life [5]. The environmental benefits of remanufacturing in the automotive sector have been reported by many researchers.

Sutherland et al. [6] found that by remanufacturing a diesel engine, a 90% reduction in energy consumption can be obtained. Dias et al. [7] also reported that 74% and 40% reductions in CO_2 emission and energy consumption, respectively, are resulted from remanufacturing a diesel engine. According to Liu et al. [8], diesel engine

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remanufacturing results in a 67% savings in global warming potential (GWP).

Research has also indicated that remanufacturing has a significant benefit from the economic standpoint. Smith and Keoleian [9] reported that the price of remanufactured engine parts is about 30% - 53% lower than the price of the newly manufactured engine parts. Similarly, Deng et al. [10] also found that that remanufacturing process results in an up to 50% cost savings.

From the above literature, it can be seen that most research compared the economic and environmental benefits of remanufacturing as a separate dimension. This paper aims to integrate and simultaneously compare the economic and environmental benefits of the remanufacturing process of automotive products in an eco-efficiency portfolio. The products being compared are a newly manufactured and a remanufactured diesel engine cylinder block.

The eco-efficiency portfolio of the cylinder bocks is constructed through a series of normalization processes. For the environmental perspective, GWP of the cylinder blocks are considered and measured using LCA methodology. For the economic dimension, the prices of the cylinder blocks are taken into account. Finally, a single value representing a combined economic-environmental benefit achieved from remanufacturing a cylinder block is presented.

2. Materials and Methods

2.1. Goal and scope definition

The goal of this study is to compare the eco-efficiency performance of a newly manufactured and a remanufactured cylinder block. The weight of the cylinder block is 260 kg and made of cast iron. The engine using the cylinder block is a WD615 diesel engine produced in China.

The manufacturing and remanufacturing processes being considered in this study are presented in Fig. 1 and 2, respectively. All processes depicted in the figures occur in China. Producing a new cylinder block and remanufacturing an old cylinder block are the functional units of this study.

Fig. 1 presents that the processes of making a new cylinder block starts with iron ore as raw material and proceeds through sintering, blast furnace, induction molding, casting, and ends with machining. The processes of preparing mold and core are not considered in this study. Furthermore, the transportation activities between processes included in Fig. 1 are also excluded from the analysis. From Fig. 2, it can be seen that the remanufacturing process is preceded by pyrolysis, shot blasting, and cleaning and followed by another cleaning and ended with inspection. Similar to the manufacturing process, transportation activities between processes involved in Fig. 2 are excluded from this study.

2.2. Life cycle inventory analysis

The inventory data of producing a new cylinder block are presented in Table 1. The inventory data related to iron ore production, sintering, blast furnace, and induction melting are calculated based on [11,12,13,14]. However, the emission data for the machining processes are generated using GaBi® software based on the information on electricity consumption provided by the manufacturer. According to the manufacturer, the price of a newly manufactured cylinder block is US$1,346.

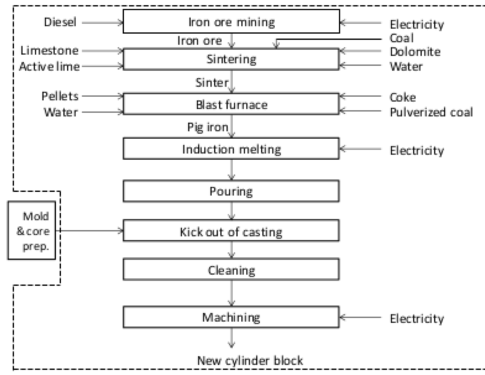

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Fig. 1. Cylinder block manufacturing process

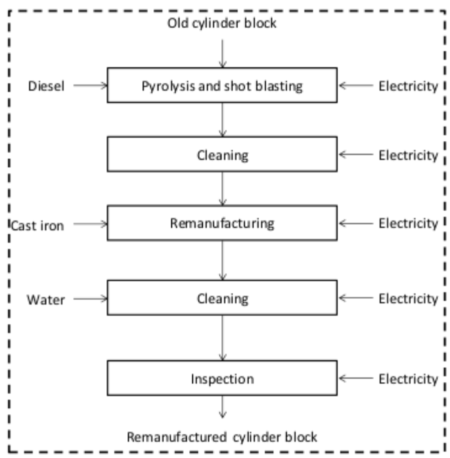

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Fig. 2. Cylinder block remanufacturing process

In Table 2, the inventory data for cylinder block remanufacturing are presented. Based on the energy consumption information provided by the remanufacturer, the emission data of the remanufacturing process are generated using GaBi® software. According to the remanufacturer, the price of a remanufactured cylinder block is US$825.

2.3. *Life cycle impact assessment*

According to ISO 14040 [15], life cycle impact assessment has the following mandatory steps: impact category selection, classification, and characterization. The environmental impact category analyzed in this study is the global warming effect of manufacturing and remanufacturing a cylinder block. In the classification step, items in the life cycle inventory tables contributing to the global warming are identified and grouped together. Global warming potential characterization factors for a 100-year time horizon (GWP100) of the IPCC 2007/2001 model [16] are utilized. For the economic dimension, the prices of the cylinder blocks are used to represent their economic impacts.

Additionally, a normalization step is also performed. Since all processes occur in China, then Chinese GWP and GDP per capita in 2012 are used as the normalization reference values. According to the World Bank [17,18], Chinese GWP per capita in 2012 is 9,221 kg CO_2-eq. and GDP per capita in 2012 is US$11,220.

Table 1. Life cycle inventory for cylinder block manufacturing

Item	Quantity	Unit
Input		
Energy and fuels		
Coke	150.94	kg
Diesel fuel	6.06E-02	kg
Electricity	420.96	kWh
Pulverized coal	3.16	kg
Materials		
Active lime	23.99	kg
Dolomite	3.74	kg
Iron ore	288.38	kg
Limestone	8.41	kg
Pellets	170.65	kg
Water	1683.79	m^3
Output		
Emissions to air		
CH_4	1.11	kg
CO	9.12	kg
CO_2	685.10	kg
N_2O	1.78E-02	kg
NH_3	9.23E-01	kg
NOx	6.042	kg
SO_2	1.64	kg
Product		
New cylinder block	260.00	kg

2.4. *Eco-efficiency analysis*

According to Kicherer et al. [19], eco-efficiency is a cross efficiency measure relating the environmental impacts of products and their economic values. It can be interpreted as the environmental impact level of a product per its monetary value. Eco-efficiency focuses on compromising economic benefits and environmental performance and its objective is to maximize economic benefits and minimize environmental impact [10]. The steps and equations presented in Kicherer et al. [19] are followed to construct the eco-efficiency portfolio of the cylinder blocks.

Table 2. Life cycle inventory for cylinder block remanufacturing

Item	Quantity	Unit
Input		
Energy and fuels		
Diesel fuel	7.50	kg
Electricity	46.00	kWh
Materials		
Cast iron	9.00	kg
Water	3.750	[illegible]
Old cylinder block	±260.00	kg
Output		
Emissions to air		
CH_4	1.22E-01	kg
CO	1.78E-01	kg
CO_2	67.24	kg
N_2O	1.95E-03	kg
NH_3	1.79E-04	kg
NO_x	7.41E-01	kg
SO_2	1.51E-02	kg
Product		
Remanufactured cylinder block	260.00	kg

The steps and equations are the following [19]:

Step 1: Calculate the relation between GWP and cost using equation (1).

$$R_{GWP,C} = \frac{\sum_{i=1}^{n} NGWP_i / n}{\sum_{i=1}^{n} NC_i / n} \quad (1)$$

Step 2: Calculate the portfolio positions using equations (2) and (3).

$$PP_{GWP,i} = \frac{NGWP_i}{\sum_{i=1}^{n} NGWP_i / n} \quad (2)$$

$$PP_{C,i} = \frac{NC_i}{\sum_{i=1}^{n} NC_i / n} \quad (3)$$

Step 3: Calculate the corrected portfolio positions using equations (4) and (5) and plot the corrected portfolio positions. The plot is known as an eco-efficiency portfolio and its structure is presented in Fig. 3. In the figure, two products are used as the illustration. From the plot, it is known that product 1 has a better eco-efficiency performance than product 2 because product 1 is located in the more favorable region (lower PP'_{GWP} and PP'_C and have a shorter distance to the origin).

$$PP'_{GWP,i} = \frac{\sum_{i=1}^{n} PP_{GWP,i} \Big/ n + \left(PP_{GWP,i} - \sum_{i=1}^{n} PP_{GWP,i} \Big/ n \right) \sqrt{R_{GWP,C}}}{\sum_{i=1}^{n} PP_{GWP,i} \Big/ n} \quad (4)$$

$$PP'_{C,i} = \frac{\sum_{i=1}^{n} PP_{C,i} \Big/ n + \left(PP_{C,i} - \sum_{i=1}^{n} PP_{C,i} \Big/ n \right) \Big/ \sqrt{R_{GWP,C}}}{\sum_{i=1}^{n} PP_{C,i} \Big/ n} \quad (5)$$

where:

i	=	index for the ith product
n	=	number of products being analyzed
$NGWP_i$	=	normalized GWP for the ith product
NC_i	=	normalized cost for the ith product
$R_{GWP,C}$	=	the relation between GWP and cost
$PP_{GWP,i}$	=	portfolio position for the GWP of the ith product
$PP_{C,i}$	=	portfolio position for the cost of the ith product
$PP'_{GWP,i}$	=	corrected portfolio position for the GWP of the ith product
$PP'_{C,i}$	=	corrected portfolio position for the cost of the ith product

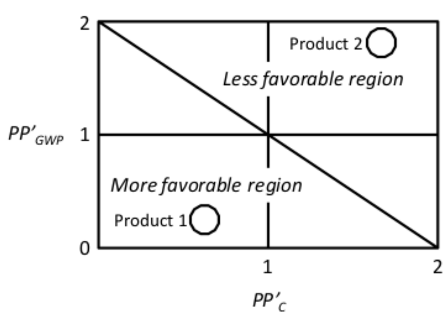

Fig. 3 Structure of eco-efficiency portfolio

3. Results and discussion

According to the inventory data, it is concluded that by remanufacturing a cylinder block, a 94% savings in energy consumption is obtained. The calculation is done using the energy content and quantity of fuels used in manufacturing and remanufacturing processes. To produce 9 kg cast iron used in the remanufacturing process, approximately a total of 9.3 kg iron ore is required. It means that approximately a 97% savings in iron ore, active lime, dolomite, limestone, and pellets consumptions is achieved. Cylinder block remanufacturing processes also results in a 57% reduction in water consumption. For the air emissions, 89%, 98%, 90%, 89%, 99%, 88%, and 99% reductions in the amount of CH_4, CO, CO_2, N_2O, NH_3, NO_x, and SO_2 emissions are also resulted.

Using GWP characterization factors for a 100-year time horizon, it is found that total GWP of a cylinder block manufacturing process is 711.38 kg CO_2 eq. and GWP of a cylinder block remanufacturing process is 69.95 kg CO_2 eq., which means that the remanufacturing process results in a 90% reduction in GWP. From the economic perspective, a savings of 39% is also achieved by remanufacturing a cylinder block.

Dividing the GWPs and prices of the newly manufactured and remanufactured cylinder blocks with the GWP and GDP per capita of China, the normalized GWP and cost of the cylinder blocks are the following:

$NGWP_{New}$	= 0.08 inhabitant
$NGWP_{Remanufactured}$	= 0.01 inhabitant
NC_{New}	= 0.12 inhabitant
$NC_{remanufactured}$	= 0.07 inhabitant

Using equations (1) - (5), the portfolio positions of the cylinder blocks are presented in Fig. 4.

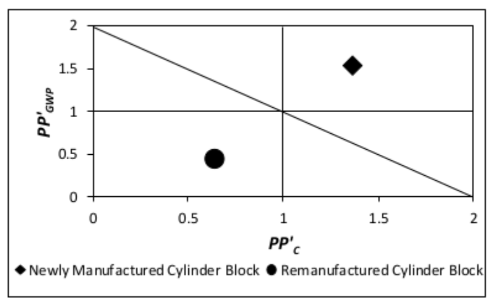

Fig. 4 Eco-efficiency portfolio of the cylinder block

From the above figure, it is clear that the remanufactured cylinder block has a better eco-efficiency performance. Since the objective is to minimize GWP and cost, then the origin of the plot is the ideal position and the distance from the plotting point to the origin indicates the eco-efficiency index of the cylinder blocks. The distance from the plotting point to the origin for the remanufactured cylinder block is 0.78 and the distance for the newly manufactured cylinder block is 2.06. It means that the remanufactured cylinder block has a better eco-efficiency performance by about 62%. The value of the relation between GWP and cost for the above plot is $R_{GWP,C}$ = 0.44, which means that, in this case study, cost is more important than GWP by about a factor of 2.

In order to generalize the eco-efficiency performance of the remanufactured cylinder block, a sensitivity analysis is conducted. The focus of the analysis is the effect of the change in the location of the manufacturing and remanufacturing processes. This implies that the reference values for the normalization process will also be changed. Due to the lack of data, the analysis assumes that the economic impact and GWP of the cylinder blocks do not change. Three scenarios are compared in the analysis:

- Scenario 1: The processes occur in lower-middle-income country and Indonesia is selected.
- Scenario 2: The processes occur in upper-middle-income country and China is selected.
- Scenario 3: The processes occur in high-income country and the U.S is selected.

The country classification is made according to the World Bank country and lending groups [20]. Note that the eco-efficiency analysis for scenario 2 is the original case study discussed in this paper and the results are presented in Fig. 4. Since, for all scenarios, the economic impact and GWP of the cylinder blocks are assumed to be the same, then the economic and GWP savings of remanufacturing for all scenarios are also the same. However, the differences in normalization value have an interesting implication. The results are presented in Table 3.

Table 3. Eco-efficiency performance of the remanufactured cylinder block according to the economic classification of the location where the processes occur

Scenario number (country)	$1/R_{GWP,C}$	% increase in eco-efficiency if the cylinder block is remanufactured
Scenario 1 lower-middle-income country (Indonesia)	2.46	62%
Scenario 2 upper-middle-income country (China)	2.28	62%
Scenario 4 high-income country (U.S)	1.12	64%

From the values of $1/R_{GWP,C}$, it can be seen that the importance levels of the economic factor (relative to the GWP) in Indonesia and China are two times the importance level of the economic factor (relative to the GWP) in the U.S. This implies that remanufacturing has a greater perceived economic benefit in the lower and middle income countries. In the opposite, the increase in eco-efficiency performance of the remanufactured cylinder blocks in the U.S. is greater than the increases for Indonesia and China. This is because of the normalized values of the GWP for the U.S. is about two and six times lower than the values for China and Indonesia, respectively. Therefore, it can be concluded that the environmental savings from remanufacturing has a higher perceived benefit in the high-income countries. These results are in accordance with the literature saying that the economic benefit will have a greater impact in the developing countries because their highest priority is the economic growth while the developed countries stress on the environmental aspect [2, 21].

It is important to note that the eco-efficiency index also depends on the quality of the data used in making the calculation [19]. The main challenge is in determining the environmental impact of the products being analyzed. The LCA method is used in this study but still the precision of the results depends on the quality of the inventory data. Therefore, the use of process based LCA is recommended [23]. Furthermore, how the boundary of the system being studied is decided also affects the precision of the inventory data. In the literature, several methodologies have been proposed to decide LCA system boundary, such as the ISO guidelines [15], RMEE method [24], hybrid method [25], and optimization approach [26,27]. Finally, when measuring the eco-efficiency, it is also suggested that the same system boundary must be used for the environmental and economic aspects.

4. Conclusions

This paper has successfully presented the environmental and economic benefits of remanufacturing a cylinder block of a diesel engine. Based on the results of the inventory analysis, it is found that remanufacturing a cylinder block results in an 88% - 99% savings in energy consumption, use of materials, and air emissions. From the economic standpoint, the price of a remanufactured cylinder block is 39% lower than the price of a newly manufactured cylinder block. In terms of GWP, the remanufactured cylinder block produces a 90% reduction. However, after normalizing the impacts, it is found that the cost is relatively more important that GWP by a factor of 2. Finally, in terms of eco-efficiency, a remanufactured cylinder block has a better performance by about 62% compared to a newly manufactured cylinder block. The results of this study are in accordance with the results of previous research stating that remanufacturing is a better end-of-life option in reducing the environmental and economic impacts of products.

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