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Exploring optimal timing for remanufacturing based on replacement theory (Article)

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Abstract

This paper presents a model to determine an optimal timing for remanufacturing from the environmental perspective. Long-run environmental impact per distance travelled $L(s_r)$ is defined based on the replacement theory. In the case study, the Weibull distribution function of crankshaft's time to failure is obtained. The $L(s_r)$ is calculated by dividing the total environmental impact with the distance travelled by the crankshaft. The minimum value of $L(s_r)$ indicates the best long-run environmental benefit. When climate change is selected as an environmental impact indicator, the result shows that the minimum value of $L(s_r)$ is achieved when the crankshaft reaches 1.53×10^5 km. © 2016 CIRP

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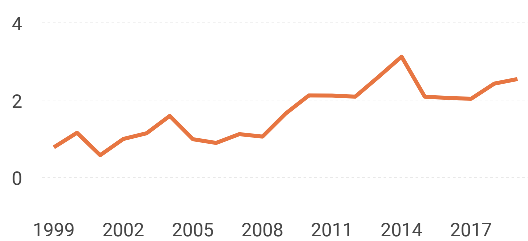

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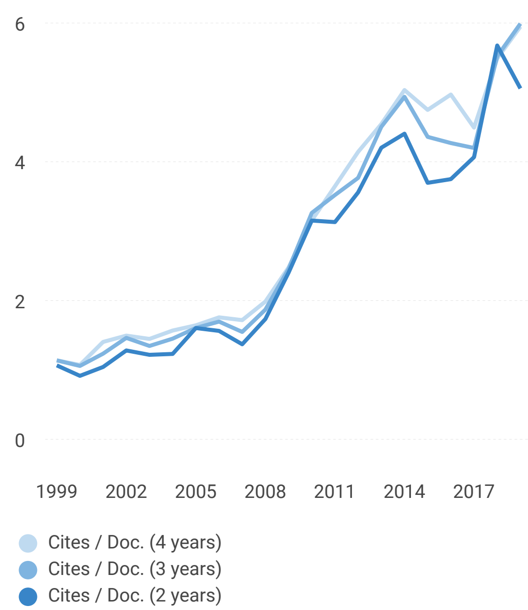

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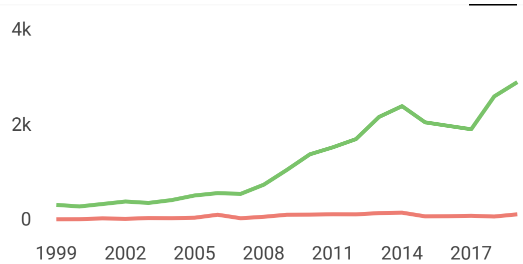

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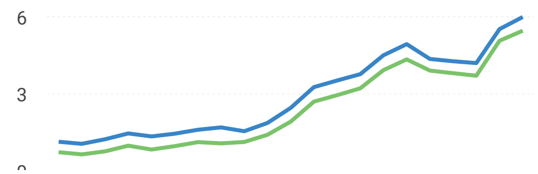

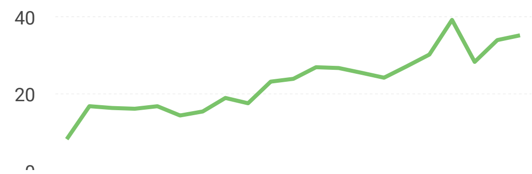

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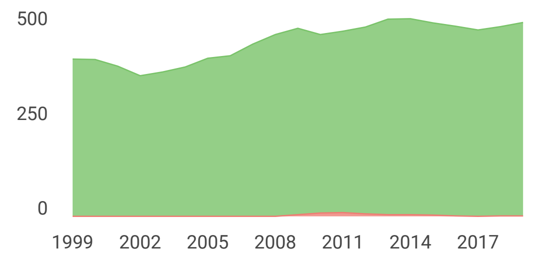

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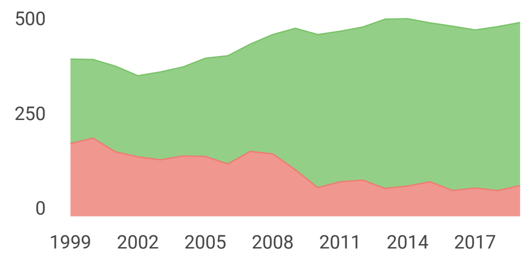

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Exploring optimal timing for remanufacturing based on replacement theory

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ABSTRACT

This paper presents a model to determine an optimal timing for remanufacturing from the environmental perspective. Long-run environmental impact per distance travelled $L(s_r)$ is defined based on the replacement theory. In the case study, the Weibull distribution function of crankshaft's time to failure is obtained. The $L(s_r)$ is calculated by dividing the total environmental impact with the distance travelled by the crankshaft. The minimum value of $L(s_r)$ indicates the best long-run environmental benefit. When climate change is selected as an environmental impact indicator, the result shows that the minimum value of $L(s_r)$ is achieved when the crankshaft reaches 1.53×10^5 km.

1. Introduction

The rapid development of building industry in China makes the demand for construction vehicles increase gradually and meanwhile, the quantity of scrapped trucks grows dramatically due to the high load operation. The manufacturing processes of large and expensive engine parts, such as the crankshaft, are energy intensive and generate large amounts of environmental emissions as well [1]. Therefore, it is essential to develop new technology to prolong the service life of high value added components.

Remanufacturing is a transformation process by which a previously failed product or component is recycled and refurbished through a series of rigorous processes, including disassembly, cleaning, inspection, repairing and reassembly, to ensure its performance meets or exceeds the new product [2]. Realizing the noticeable environmental and economic benefits, automobile products remanufacturing has become dominant in the field and occupies two-third of all remanufacturing in the US and the market has ballooned into the industry involving more than USD 100 billion worldwide [3]. Several reports have documented the overall benefits of engine components remanufacturing [4–6], all of which have indicated that remanufacturing could remarkably reduce the energy and resource consumptions and environmental emissions. However, the remanufacturing timing selection is rarely mentioned in these reports, and the benefits of remanufacturing might be quite different when it is remanufactured at a different point in time.

End-of-life (EoL) remanufacturing is regarded as a general ideology for remanufacturing as it can achieve the biggest product use value. Several models have been built to optimize the EoL remanufacturing system [7] and support the design for EoL remanufacturing [8]. Some researchers consider that the end-of-life product remanufacturing is a good idea as it can reach the maximum value of the product [9]. However, when the product already reaches the end of its life and is completely obsolete, the remanufacturing process will consume more energy and produce much more pollution.

"Active remanufacturing" is proposed aiming to solve the uncertainties of cores in remanufacturing procedure, and prolong the product life cycle and eliminate the cost and environmental burdens during the components remanufacturing processes [10]. "Active remanufacturing" requires that the product be remanufactured once it has reached the prescribed time-point even though it has not been scrapped. Because the remanufacturing processes for the product at this point are relatively simple, it can reduce the energy of remanufacturing processes and improve the comprehensive efficiency along the product's entire life cycle [11].

A crankshaft is an important component of an engine and its repair or replacements is common because its surface would be easily worn due to the impurity of oil and uneven stress of the shaft neck. Traditionally, a crankshaft will be remanufactured at the same time as the engine's EoL remanufacturing takes place. This consumes more energy and produces more environmental emissions. This study aims to determine an optimal timing for the crankshaft remanufacturing from the environmental perspective. Also, the study tries to achieve the best environmental benefit and also provides an effective reference to guide engine remanufacturing practices.

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2. Materials and methods

2.1. Proposed model

A single component of a particular truck is considered during modelling. The policy of the remanufacturing process is that "the component will be remanufactured as soon as it fails or when it reaches a pre-specified distance travelled by the engine, whichever happens first." which is similar to the concept of age replacement model. Therefore the model is developed according to this concept [12]. It is also important to state that the model presented in this paper is dedicated for the continuous time to failure random variable. Graphically, the schematic diagram of the policy is presented in Fig. 1 (adapted from [12]).

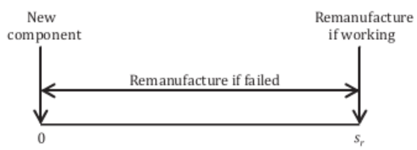

Fig. 1. Schematic diagram of the remanufacturing policy.

In Fig. 1, s_r is the remanufacturing distance such that if the component fails before s_r, it is remanufactured; if the component still works at s_r then it will be remanufactured immediately. s_r is acting as the decision variable. Since some components fail before s_r and other components still work at s_r then, based on [12], the expected total environmental impact is defined in Eq. (1):

$$E[\text{Total environmental impact for } s \le s_r] = I_r + I s_r \Pr\{S \le s_r\} = I_r + I s_r F(s_r) \quad (1)$$

In Eq. (1), S is a random variable denoting the distance travelled when the component fails (km) and its cumulative distribution function (CDF) is $F(s)$; I_r is the environmental impact from component remanufacturing processes (CO_2 equiv./component, MJ/component, kg CFC_{-11} equiv./component, etc.); I is the environmental impact produced during the component operation period (CO_2 equiv./km, MJ/km, kg CFC_{-11} equiv./km, etc.).

In Eq. (1), $\Pr\{S \le s_r\} = F(s_r)$ is the cumulative probability that the lifetime of the component will be less than or equal to s_r. It is easy to see that it is also the CDF of S with s_r as the upper limit.

Given that the remanufacturing process will be conducted as soon as the component fails or as soon as it reaches s_r, whichever happens first, then, based on [12], the actual remanufacturing distance is given by Eq. (2). The CDF and the expected value of X are given by Eqs. (3) and (4), respectively [12].

$$X = \min\{S, s_r\} \quad (2)$$

$$G(x) = \Pr\{X \le x\} = \begin{cases} F(x) & \text{if } x < s_r \\ 1 & \text{if } x \ge s_r \end{cases} \quad (3)$$

$$E[X] = E[\min\{S, s_r\}] = \int_0^\infty (1 - G(x))dx = \int_0^{s_r} (1 - F(x))dx \quad (4)$$

The objective function of the model is the long run average environmental impact per distance travelled (CO_2 equiv./km, MJ/km, kg CFC_{-11} equiv./km, etc.), denoted as $L(s_r)$, and it is modelled as the following equation.

$$L(s_r) = \frac{I_r + I s_r F(s_r)}{\int_0^{s_r} (1 - F(x))dx} \quad (5)$$

In order to find the value of s_r that will minimize $L(s_r)$, s_r^*, following [12], take the first derivative of $L(s_r)$ with respect to s_r and set it equal to zero, which yields $d(L(s_r))/ds_r = 0$.

Then, we have the following equation.

$$[I F(s_r) + I s_r f(s_r)] \int_0^{s_r} (1 - F(x))dx = [I_r + I s_r F(s_r)][1 - F(s_r)] \quad (6)$$

where, $f(\cdot)$ is the probability density function (PDF) of the component's lifetime. By dividing both sides of Eq. (6) with Is_r and $1 - F(s_r)$ and then set I_r/I as the left-hand side, Eq. (7) is produced.

$$\frac{I_r}{I} = \left[\frac{F(s_r)}{1 - F(s_r)} + s_r h(s_r)\right] \int_0^{s_r} (1 - F(x))dx - s_r F(s_r) \quad (7)$$

In Eq. (7), $h(s_r)$ is given by Eq. (8). In reliability theory, $h(\cdot)$ is known as the hazard function. Hazard function calculates the failure rate as the interval tends to zero. For this model, $h(s)$ computes the failure rate as $\Delta s \to 0$. It is assumed that the failure rate increases as s increases.

$$h(s_r) = \frac{f(s_r)}{1 - F(s_r)} \quad (8)$$

To see whether Eq. (7) has one or more than one solutions then the derivative of I_r/I with respect to s_r needs to be found and it is given by the following, Eq. (9).

$$\frac{d}{ds_r}\left(\frac{I_r}{I}\right) = \left[\frac{f(s_r)}{(1 - F(s_r))^2} + h(s_r) + s_r \frac{dh(s_r)}{ds_r}\right] \int_0^{s_r} (1 - F(x))dx \quad (9)$$

Since it is assumed the failure rate increases as s increases then $h(\cdot)$ is an increasing function. Consequently, Eq. (9) is positive for all $s_r \ge 0$. This implies that Eq. (7) is also an increasing function. Using this fact, it is expected that, if the left-hand side of Eq. (7) (a constant) and the right-hand side of Eq. (7) are plotted then the result is presented in Fig. 2, which presents only one optimal solution.

This paper applies exponential and Weibull distributions on Eq. (7). This is done because their random variables could well describe the distribution model of product life.

(i) For an exponential distribution with the parameter λ, the CDF is $F(s_r) = 1 - e^{-\lambda s}$, and the hazard function is $h(s_r) = \lambda$. Substituting the CDF and hazard function into Eq. (7) yields,

$$\lambda \frac{I_r}{I} + 2 = e^{\lambda s_r} + e^{-\lambda s_r} \quad (10)$$

(ii) For the Weibull distribution with shape parameter k and scale parameter λ, its CDF is $F(s_r) = 1 - \text{EXP}[-(s_r/\lambda)^k]$, and hazard function is $h(s_r) = (k/\lambda)(s_r/\lambda)^{k-1}$. Substituting the CDF and hazard function into Eq. (7) yields,

$$\frac{I_r}{I} = \left[e^{(s_r/\lambda)^k} + s_0 \frac{k}{\lambda}\left(\frac{s_r}{\lambda}\right)^{k-1} - 1\right] \int_0^{s_r} e^{-(x/\lambda)^k} dx + s_r e^{-(s_r/\lambda)^k} - s_r \quad (11)$$

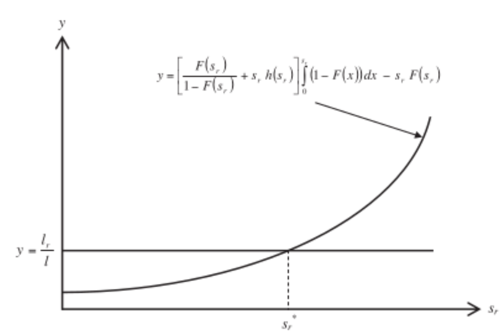

Fig. 2. Graphical solution of Eq. (7) where s_r^* is the optimal remanufacturing distance.

2.2. Sensitivity analysis

Fig. 3 shows that if s_r^* increases then the value of l_r/l will also increase and vice versa. There are several scenarios that can occur so that l_r/l increases or decreases and it is summarized in Table 1. The change in the value of l_r is due to the condition of the crankshaft to be remanufactured. A higher value of l_r means a crankshaft with a worse condition implied that it has been used for a longer driving distance.

Case 1. Since the environmental impact of the remanufacturing process increases then a longer value of s_r^* is needed so that the environmental impact per distance travelled is minimized.

Case 2. It is better to have a longer s_r^* because the component's environmental impact during use phase decreases but the environmental impact of the remanufacturing process is constant so that the total environmental impact per distance travelled is minimized.

Case 3. Since the environmental impact of the remanufacturing process decreases and the environmental impact during use phase is constant then increasing the frequency of remanufacturing process (by decreasing s_r^*) is a better option. Therefore, total environmental impact per distance travelled will be minimized.

Case 4. Since the use phase has more environmental impact then it is better to decrease s_r^*.

However, it is also essential to know the change in the magnitude of l_r/l if s_r changes. The general equation is given by Eq. (9). For exponential and Weibull distribution, the expression for $d(l_r/l)/ds_r$ is given by Eqs. (12) and (13), respectively. Those two equations confirm the conclusion made using Fig. 2, Eq. (7) is an increasing function.

$$\frac{d}{ds_r}\left(\frac{l_r}{l}\right) = e^{\lambda s_r} - \frac{1}{e^{\lambda s_r}} > 0 \tag{12}$$

$$\frac{d}{ds_r}\left(\frac{l_r}{l}\right) = \left(h(s_r)\int_0^{s_r} e^{-(x/\lambda)^k}dx\right)\left(e^{(s_r/\lambda)^k} + k\right) > 0 \tag{13}$$

Table 1
Scenarios for sensitivity analysis.

Case	l_r	l	l_r/l	Effect on s_r^*
1	Increases	Constant	Increase	Increase
2	Constant	Decrease	Increase	Increase
3	Decrease	Constant	Decrease	Decrease
4	Constant	Increase	Decrease	Decrease

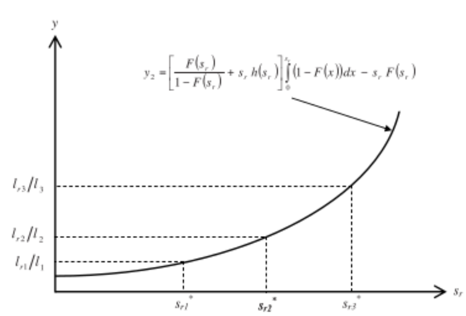

Fig. 3. The relationship between s_r and l_r/l.

3. Case study

3.1. Parameters of the model

In this study, a typical crankshaft (45#steel, 103 kg) from a WD615 Diesel engine is chosen as a case to prove the applicability of the model. Life cycle assessment (LCA) method is conducted to calculate the environmental impact of the crankshaft remanufacturing and operation [13]. To simplify the modelling process, only Global Warming Potential (GWP) is considered. The crankshaft was remanufactured in SINOTRUK, Jinan Fuqiang power Co., LTD. The energy consumptions and additional materials required during the crankshaft remanufacturing processes are shown in Fig. 4.

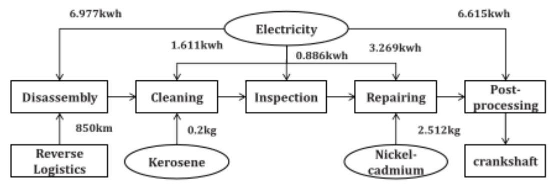

Fig. 4. Flow diagram of the crankshaft remanufacturing processes.

When the truck is in service, its fuel efficiency is 25 L/100 km. Given that the density of diesel fuel is 0.85 kg/L, then the amount of diesel fuel consumed is $0.85 \times 25/100 = 0.2125$ kg/km.

The direct contribution of each pollutant to GWP, such as CO_2, CH_4, N_2O, etc., generated in the production of materials and energy as well as scraped engine sending back is quantified according to the Chinese Life Cycle Database (CLCD) developed by IKE, China [14]; The input parameters are listed in Table 2 indicating that $l_r = 126.92$ kg CO_2 equiv. To estimate the contribution of the crankshaft to the GWP of the engine during use phase, weight to fuel economy correlation found in [15] is used and it is found that $l = 9.19\text{E}{-05}$ kg CO_2 equiv./km.

Statistical analysis of the fatigue failure rate of 100 crankshafts indicates that the rate fits Weibull distribution. The reliability curve of the crankshafts is showed in Fig. 5.

Table 2
Result of GWP during crankshaft use phase and remanufacturing process.

Items	Quantity (kg)		Characterization factor [16]	Result (kg CO_2 equiv.)	
	Reman.	Operation		Reman.	Operation
CO_2	111.65	0.226	1	126.92	0.23
CH_4	0.50	2.27E−04	25		
N_2O	0.0093	5.65E−06	298		

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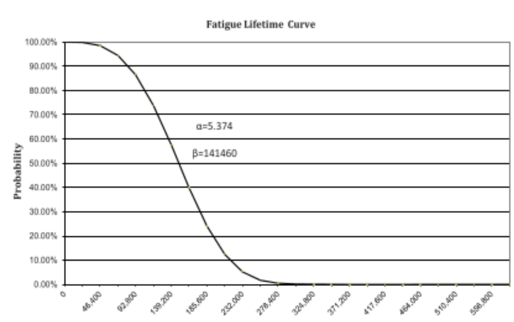

Fig. 5. Weibull Distribution for crankshafts.

3.2. Result and discussion

By substituting the value of l_r, l and the time to failure distribution function of the crankshaft into the Eqs. (5) and (7), we can draw the plot of objective function and l_r/l, as is shown in Fig. 6. From the figure it is concluded that the optimal timing for crankshaft remanufacturing is when it reaches 1.53×10^5 km of service. The minimum GWP over the whole life cycle is equal to 1.08×10^{-3} kg CO_2-equiv./km. The case study selects climate change as the environmental indicator. However, it is important to note that the model might produce other locations of optimal driving distance if other indicator, such as toxicity from metal emissions or particle effects on human health, is chosen.

The determination of an optimal remanufacturing timing for engine parts is complicated due to the difference in failure modes and service life of the components. Liu et al. analyzed the optimal timing of total engine remanufacturing by creating a model to reflect the average environmental impact over two life cycles [17]. However, the authors did not consider the reliability of the components being analyzed and excluded the effect of uncertainty in time to failure. The proposed model considers the specific failure rate the single part, and once the failure modes of all components are figured out, it could help to determine the best opportunity to each point without introducing any uncertainties, resolving the above-mentioned problem nicely.

Several aspects, such as environmental impact, economic benefit and current technology level, should be evaluated when formulating the strategy for formulating a strategy for sustainable engine parts manufacturing. Although the proposed methodology does not consider other factors except for the environmental impact, it provides a fundamental model which brings a high ability to realize the integration of all qualified aspects in the future.

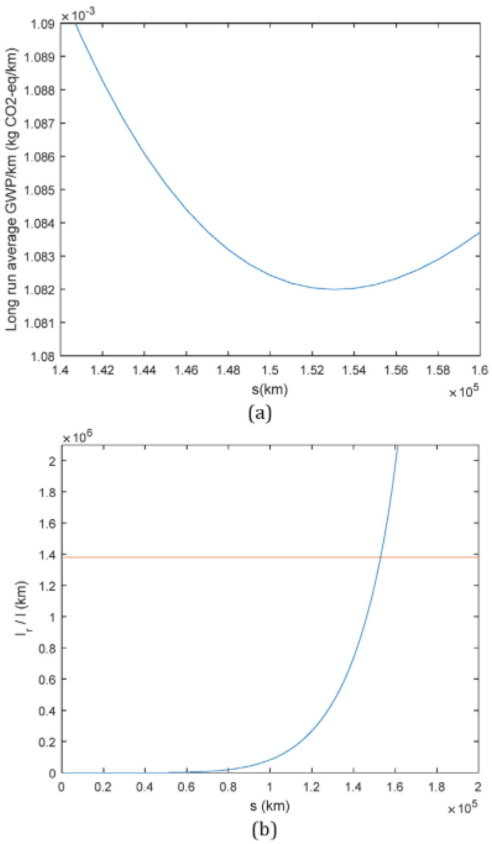

Fig. 6. Objective function plot (a) and l_r/l plot (b).

4. Conclusions

Remanufacturing can retain the surplus added value of original manufactured components. It does not only improve the performance of specific part and prolong the service life cycle but also saves resources and energy and reduces the production cost. Choosing a different time for remanufacturing can result in a different amount of environmental benefits. This paper presented a model, based on the replacement model, to figure out an optimal remanufacturing timing. A case study using the crankshaft as an object showed that the proposed model can be used to identify the best opportunity for remanufacturing. The simulated result indicated that the best environmental benefit can be achieved when the crankshaft is remanufactured after being used to drive for 1.53×10^5 km.

However, the proposed model cannot be applied to all situations. There might be unusual damage to the crankshafts causing them to be inappropriate for repair under the present technical conditions. Therefore, a re-manufacturability assessment before making a decision for remanufacturing is indispensable. The method can be used as a basic tool to better inform the decision makers. It must be said, though, in order to simplify the calculation process, only environmental impact (GWP) is considered in the case study. A more comprehensive and well balanced decision should include other decision criteria, such as cost and technology. In this case, the preference of the decision makers will play an important role.

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