Research article

Condition-based maintenance policy for a leased reman product

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ABSTRACT

Many firms prefer to lease rather than to buy a product as leasing does not require a large investment cost. Leased products can be brand new products or remanufactured products (henceforth referred to as reman products). The market of reman products has grown in the last two decades due to the increasing concern of sustainability issues. This in turn brings a positive impact on the demand of leased reman products. In general, the reliability of the reman product is closed to the reliability level of a new product. To guarantee a high performance of a leased reman product, a more effective maintenance strategy is required. In this paper, we investigate a condition-based maintenance (CBM) policy to be used for maintaining a lease reman product. With the CBM policy, the condition of the reman product is monitored and controlled periodically, and hence it can avoid failure before it occurs and reduce unnecessary maintenance actions. This in turn improves the performance of the leased reman product and provides more value to the lessee. The lessor will incur a penalty cost if the performance is below a predefined threshold value. We obtain the optimal inspection interval minimizing the expected total cost and provide the numerical example for illustrating the optimal solution.

1. Introduction

In the last decades, many firms prefer to lease rather than to purchase a product [1]. The main drives of leasing include no initial investment required, many options available for product upgrading, and maintenance and inventory cost reduced. A lot of researchers have investigated lease contracts from various aspects, and an excellent review can be found in [2]. The lease contracts studied in the literature can be done from (i) the lessor's point of view or (ii) the lessee's point of view. From the lessor viewpoint, decision problems comprise of two levels -i.e. the strategic level (dealing with type and number of product leased, upgrade options due to technological obsolescence, etc.) and the operational level (consisting of maintenance servicing, spare part stock, crew size, etc.). From the lessee viewpoint, the essential decision problems are to select the favourable product to lease from several brands available, and to seek the best lease option from the options offered. There are two types of lessees -i.e., individual households (wanting to lease consumer products e.g., washer, dryer, cars, etc.) or businesses (looking for industrial products to be leased e.g., dump truck, excavator, etc.).

Leased products can be brand new products or reman products (henceforth referred to as reman products). The market of reman products has grown in the last two decades due to the increasing concern of sustainability issues. Many components of a reman product originate from a recovery process of the used product, and hence remanufacturing consumes a much reduced amount of energy and produces in much less waste [3]. For instance, the amount of energy saving from remanufacturing of machine tools can be more than 80% ([4, 5, 6, 7]).

As a result, buying or leasing a reman product will result in a significant saving of our natural resource (https://www.curvature.com/GreenIT) and lead to a green economy in which resource and waste are reduced by the recovery process of the used products (e.g., remanufacturing, refurbishing, and recycling) [8].

Remanufacturing operations (involving disassembly, cleaning, testing and replacing parts) will improve a used product to a like-new quality level ([9, 10]). In other words, the reliability of a reman product will be
at least the same level of the reliability required \( R_m \) but it is just lower than the reliability level of a new product \( R_n \) \[10\]. The reliability of reman products is expected to fall between \( R_m \) and \( R_n \) as the remanufacturing process involves some uncertainty with regard to the quality of the products at the end of the first use \[11\].

Recently, many reman heavy product (such dump trucks, excavators) are offered in the market \([12, 13]\) due to the increasing concern of the sustainability issues, and the economy benefit (a profit margins earned from the remanufacturing business is quite high (i.e., about 20\%)). The price of reman product is 30\%–40\% less than the price of new product, and this make the price of a LC for a reman product reasonable lower than the price of a LC for a new one. Hence, the LC of a reman product becomes a good alternative option for customers \[14\].

To maintain the leased product in a high performance, an effective maintenance strategy is a must. A maintenance strategy used by the lessor can be categorized into two group – i.e., a time-based maintenance (TBM) policy or a condition-based maintenance (CBM) policy \[15\]. A lot of LCs consider a TBM policy to keep the product in good performance. PM actions can be based on (i) a constant interval (called a periodic PM policy) or (ii) a non-constant interval (called a sub-sequential PM policy). Furthermore, each PM policy can be subdivided into two categories – i.e., PM policies dealing with (i) a single component system and (ii) a multi-component system \([16, 17, 18, 19]\). studied the LC for a single component system with a periodic PM policy. Whilst \[20\] and \[21\] examined LCs for a single component system with a sub-sequential PM policy. These papers consider a LC for a new product. LCs for used and reman products can be found in \[22, 23\] and \[10\], for example.

The aforementioned LC papers consider a TBM policy, which often results in unnecessary maintenance actions as it is based on age and/or usage and does not consider the condition of a product \[24\]. To improve the effectiveness of the maintenance actions, a CBM policy is used to monitor and control the performance (e.g., availability) of the leased product. CBM is a maintenance policy in which the maintenance (PM or CM) action is dependent on the condition of the product \[25\].

With CBM, the product condition needs to be characterized through a set of parameters (e.g. vibration, temperature, quality of lubricating oil, and noise levels), and the data of the parameters are gathered by using various sensors periodically or continuously \[26\]. This allows us to monitor the condition (or degradation level) of the product and decide a maintenance action (CM or PM) based on the condition monitored -i.e. if the degradation level is closed to the failed state, a PM action is carried out or if the degradation level exceeds a failed state, a CM action is done \[27\]. As a result, failure can be detected before it occurs, and hence it can reduce failure and unnecessary maintenance actions, and this in turn decrease the downtime of the product and the maintenance cost.

Furthermore, the CBM policy can be classified into two categories (as in the TBM policy) – i.e., CBM policy for (i) a single-component system and (ii) a multi-component system. Most of CBM studies in the literature focus on single-component systems (see \[25, 28, 29\]) where a PM is done if the degradation level falls in PM region.

For a multi-component system, the component dependencies need to be considered in formulating the CBM policy. A recent review can be found in \[30\]. There are three types of dependencies: (i) economic, (ii) stochastic and (iii) structural. The dependency of type (i) exists when a component is affected by the degradation of another component \([31, 32]\). The dependency of type (ii) occurs if the degradation of one component affects the degradation of another component \([33, 34]\). The dependency of type (iii) takes place if some components need to be maintained simultaneously \[35\].

However, the application of CBM for maintaining a leased product has received little attention. We are aware only the work of \[36\] who proposed a CBM policy to control the condition of the leased new product aiming to increase availability and performance of the product. Therefore, CBM is expected to improve the satisfaction of lessees and the sale volume. In this, the leased new product is considered as a single component system and the degradation level is modelled using one degradation process.

In this paper, we consider a LC for reman product, in which the CBM is used to guarantee a performance stated in the contract. As CBM is able to detect failure prior to its occurrence, regardless a product is a brand new or a reman product. As a result, the performances of the leased reman product and the leased new product when using CBM would be very similar. The difference between the two options lies in the cost to perform CBM – i.e., the CBM cost for a reman product is slightly higher (as it needs more inspections) than the cost for the new one. But due to the price of the reman product is much lower (at least 40\% cheaper), then the LC for the reman product with CBM still has a cost advantage and becomes an attractive option for the lessee – in terms of a lower price and yet high performance.

Using CBM, it is required to model the degradation level of the product. There are two approaches to modelling the degradation level -i.e., (i) one degradation process or (ii) a multiple degradation processes. For (i), stochastic processes used include the Gamma process \([37, 38]\), the Wiener process \[39\], the inverse Gaussian process \[40\], and the Ornstein-Uhlenbeck process \[41\]. However, the Gamma process is a widely applied to represent the degradation in the literature. For (ii), it is considered that a system experiences a multiple degradation processes causing the system failure \([42, 43, 44]\), to name a few.

This paper investigates the situation where the leased product is operated in various environment conditions (light, moderate and heavy operating conditions), and the usage (distance travelled) of the product can vary across the population of the lessees. These factors, in turn, will affect the rate of the degradation of the product. As a result, we need to consider the usage and operating conditions in modelling the degradation condition of the product.

The Gamma process will be applied to model the degradation of the reman product in the LC period. The variability of the degradation level (due to the effect of the usage and operating conditions) can be modelled through (i) the scale parameter or (ii) the shape parameter of the Gamma process \[12, 45\] used (i) to modelling the variability due to random effects through the scale parameter considered as a random variable following a Gamma distribution. One can easily incorporate covariates by formulating the scale parameter as a function of a random variable and covariate. Moreover, this proposed Gamma degradation model was tested by \[46\] for the existence of a variability in the degradation rate across a population of products.

The alternate approach is to model via the shape parameter (defined as a function of the age (\( t \)) and covariates (\( x \))) and then use the AFT model (Accelerated Failure Time) allowing us to incorporate the age and covariates (e.g., usage and operating condition). Hence, the shape parameter is defined as \( a(t; x) \) \[47\]. considered the AFT model for formulating \( a(t; x) \). In this paper, we will use a different AFT model, which is appropriate for the situation considered, and this will be described in Section 2.

The main contributions of this paper are (i) to develop a model for representing the degradation process of the leased reman product operated in various usage patterns and environment conditions, in which the effect of the usage patterns and operating conditions is modelled through the shape parameter, and (ii) to seek for the optimal solution of the CBM policy using the degradation model developed in (i).

The structure of this paper is as follows. Section 2 deals with the model formulation and assumptions. Section 3 presents the CBM policy studied and the expected total cost of the CBM policy. In Sections 4 and 5, we present the optimization of the CBM policy and the numerical example, respectively. Finally, the conclusions and further research are described in Section 6.

2. Model description and assumptions

This paper uses the following notations:
2.1. Lease contract

We consider a leased reman product (such a dump truck in which its major sub-systems such as engines, transmissions, power modules, etc. are reman components). The lessor offers a lease contract for such a dump truck for period of \( L \). During the lease contract period, maintenance activities consisting of PM, CM and inspection to monitor the condition of the truck are performed by the lessor. To provide a positive signal to the lessee with regard to the leased reman product, the lessee promises a high availability of the leased product. A penalty cost incurred to the lessor if the performance is below a predefined threshold of availability.

2.2. Degradation modelling

The condition of the leased product is characterized by the level of degradation due wear as in [36]. We consider that the leased product deteriorates with the age, usage and operating condition of the product, and ultimately the product fails when the degradation level (represented by the accumulation of wear) exceeds a critical level.

As mentioned in Section 1, the Gamma process is applied to modelling the product’s deterioration (or degradation). Let \( Z(t) \) denote the degradation level at time \( t \). [\( Z(t), t \geq 0 \)] is a stochastic process which is continuous and monotonically increasing of \( t \) with \( Z_0 = 0 \). Here, it is assumed that \( Z(t), t \geq 0 \) is a Gamma process with scale parameter \( \beta \)(> 0) and shape parameter \( \alpha(t) \) which is continuous and non-decreasing function of \( t \) with \( \alpha(0) = 0 \). The pdf of \( Z(t) = z \) is

\[
g(z; \alpha(t), \beta) = \frac{\beta ^ {\alpha(t)} e^{-z/\beta}}{\Gamma(\alpha(t))} (1)
\]

The increment \( Z(t) - Z(s) \) (for all \( s \leq t \)) is independent and follows the Gamma distribution with pdf given by (1).

Now, the effect of the age, usage, and operating condition is modelled via the shape parameter of the Gamma process. It is considered that the reman product has a nominal usage \( (u_0) \). If the usage is high (or \( u > u_0 \)) then the deterioration goes faster, otherwise it moves slower. Let \( U_0(t) \) be the shape parameter of Gamma process \( Z(t) \) for a given usage \( u \). Then \( U_0(t) \) is,

\[
a_0(t) = \eta(u, \rho) \alpha(t),
\]

where \( \eta(u, \rho) = \left( \frac{1}{u} \right)^\rho \) represents the AFT factor which is a function of the usage \( u \) and operating condition \( \rho \). The product is operated under a stressful environment (e.g., a dump truck transports mining materials in a high inclined road) will experience more stress, and this is represented with \( \rho > 1 \) whilst \( \rho = 1 \) represents a normal (or moderate) operating condition (e.g., a relatively flat road). Hence, \( a_0(t; \rho > 1) > a_0(t; \rho = 1) \) for a given usage rate \( u \) or the deterioration rate under the more environment is very much higher than that under a normal one.

As a result, the increment degradation\( Z(t) - Z(s) \), follows the Gamma distribution with pdf given by (1) replacing the shape parameter \( \alpha(t) \) with \( a_0(t) \). Note that the AFT model in (2) is more appropriate to be used for this context compared with that developed by [47] i.e., \( g(x; \alpha(t), \beta) = \frac{\beta ^ {\alpha(t)} e^{-x/\beta}}{\Gamma(\alpha(t))} \) where \( \alpha(t) \) is the vector of regression and \( x \) covariates (e.g., the usage and operating conditions).

2.3. Modelling failure of reman product

In general, the reliability of a product at the end of the first use is relatively low (or the reliability is substandard or less than the standard). Remanufacturing process makes the reman product’s reliability to increase, since all parts of the reman product have been tested and passed the quality testing. We consider that after the remanufacturing, the reliability of the product gets improved in the sense that it reduces the virtual age of the product [48]. As a result, at the end of the first life of the product, \( \tau_1 \), the virtual age will reduce to \( (1 - \delta) \tau_1 \) where \( \delta \) is the improvement factor. As a result, the degradation level of the reman product at the beginning of a lease period, \( t = 0 \) and \( \tau_1 \) is not zero, but it is equal to \( (1 - \delta) \tau_1 \). Note that a new product has \( Z(0) = 0 \) and \( t = 0 \).

It is assumed that the reman product undergoes condition inspection at \( k = 1, 2, \ldots \). Let \( Z(t_0 - 1) \) and \( Z(t_k) \) denote the deterioration level at \( t = t_0 - 1 \) and \( t_k \) respectively. Define, the degradation increment in interval \( (t_0 - 1, t_k) \), \( \Delta Z_k = Z(t_k) - Z(t_0 - 1) \). Then the pdf of \( \Delta Z_k \) is given by

\[
f_{\alpha_0(t_k-t_{k-1})}(\Delta Z_k) = \frac{\beta^{\alpha_0(t_k-t_{k-1})} \exp(-\beta \Delta Z_k)}{\Gamma(\alpha_0(t_k-t_{k-1}))} (3)
\]

The expected deterioration growth in \( (t_0 - 1, t_k) \) for a given \( \rho = \rho \alpha_0(t_k-t_{k-1})/\beta \). Define,

\[
F_k(x) = \int_0^x f_{\alpha_0(t_k-t_{k-1})}(y)dy
\]

Then,

\[
P(\Delta Z_k > z, L_k > z) = 1 - P(\Delta Z_k \leq z)
\]

\[
F(\tau - z) = P(\Delta Z_k \leq z) = \int_0^{\tau - z} f_{\alpha_0(t_k-t_{k-1})}(y)dy
\]

Let \( L_0 \) denote the degradation of the reman product at \( t = 0 \). As the reman product is not as good as a new one, then \( L_0 \) is given by \( L_0 = E[Z(1 - \delta) \tau_1] \) which is the mean of \( Z(t = 1 - \delta) \tau_1 \). One can estimate \( L_0 \) if \( \tau_1 \) (the first life of the product) and \( \delta \) (the improvement factor) are available. The value of \( \tau_1 \) is obtained from the product record data, but \( \delta \) needs to be estimated using failure data of the reman product.

The reliability function of the reman product at time \( t \) is given by

\[
T(t) = T(Z(t) < L) = T(Z(t) = L_k = L_k - L_0)
\]

\[
= \int_{L_k}^{L_0} \left[ \frac{\beta^{\alpha_0(t_k-t_{k-1})} \cdot \exp(-\beta \Delta Z_k)}{\Gamma(\alpha_0(t_k-t_{k-1}))} \right] d\Delta Z_k
\]

Define \( V = \Delta Z_k \), then we have

\[
P(Z(t) < L_k) = \int_{L_k}^{L_0} \left[ \frac{\beta^{\alpha_0(t_k-t_{k-1})} \cdot \exp(-\beta V)}{\Gamma(\alpha_0(t_k-t_{k-1}))} \right] dV
\]

\[
= \int_{L_k}^{L_0} \frac{1}{\Gamma(\alpha_0(t_k-t_{k-1}))} \int_{L_k}^{L_0} \beta^{\alpha_0(t_k-t_{k-1})} \cdot \exp(-\beta V) dV.
\]

Figure 1 shows that the degradation level \( Z(t_k) \) at \( t_k \) is still below \( L_0 \) and at \( t_k \) (the next inspection point) can be in the PM state i.e., \( L_p <
$Z(t_{k}) \leq L_{p}$ or in failed state $Z(t_{k}) > L_{f}$. The increased in the degradation level defines the value of $\Delta Z_{k}$.

We now find the probability of failure in $[t(k-1), t(k)]$ is obtained as follows.

$$P\{Z(t_{k}) > L_{f} \mid Z(t_{k-1}) \leq L_{p}\} = P\{Z(t_{k}) > L_{f} \mid Z(t_{k-1}) \leq L_{p}\} \times P\{Z(t_{k-1}) \leq L_{p}\}$$

where,

$$P\{Z(t_{k}) > L_{f} \mid Z(t_{k-1}) \leq L_{p}\} = \int_{L_{p}}^{\infty} P\{Z(t_{k}) > L_{f} \mid Z(t_{k-1}) = z\} \times p_{k-1}(z|z < L_{p}) \, dz$$

$$p_{k-1}(z|z < L_{p}) \approx \frac{P\{Z(t_{k-1}) = z\}}{P\{Z(t_{k-1}) < L_{p}\} - P\{Z(t_{k-1}) < L_{p}\}}$$

$$s_{k-1}(z) = \frac{\beta^{\alpha(k-1)-1} \cdot \exp(-\beta z) \cdot dz}{\Gamma(\alpha(k-1))}$$

and $G_{k-1}(z)$ is the CDF associated with $X_{k-1}(z)$.

Since

$$P\{Z(t_{k}) > L_{f} \mid Z(t_{k-1}) = z\} = P\{\Delta Z_{k} > L_{f} - z\} = 1 - F_{k}(L_{f} - z)$$

and $F_{k}(z)$ is the distribution function of $\Delta Z_{k}$ over the interval $[k-1, k]$. From (6), then we have,

$$P_{k}^{t} = P\{Z(t_{k}) > L_{f} \mid L_{0} < Z(t_{k-1}) \leq L_{p}\} = \int_{L_{p}}^{\infty} \{1 - F_{k}(L_{f} - z)\} s_{k-1}(z) \, dz$$

Note that $P_{k}^{t}$ for $k = 1$ is given by

$$P_{1}^{t} = P\{Z(t_{1}) > L_{f} \mid L_{0} < Z(t_{0}) = L_{0}\} = 1 - F_{1}(L_{f} - L_{0})$$

The probability of PM at $t_{k}$

$$P\{L_{0} \leq Z(t_{k}) < L_{f} \mid L_{0} < Z(t_{k-1}) \leq L_{p}\} = P\{L_{0} \leq Z(t_{k}) < L_{f} \mid L_{0} < Z(t_{k-1}) \leq L_{p}\} \times P\{Z(t_{k-1}) \leq L_{p}\}$$

Nothing that

$$P\{L_{0} \leq Z(t_{k}) < L_{f} \mid L_{0} < Z(t_{k-1}) = z\} = P\{L_{0} < z < \Delta Z_{k} < L_{f} - z\}$$

$$= \int_{L_{0}}^{L_{f} - z} F_{k}(L_{f} - z) \, dz$$

Then,

$$P_{k}^{t} = P\{L_{0} \leq Z(t_{k}) < L_{f} \mid L_{0} < Z(t_{k-1}) < L_{p}\} = \int_{L_{0}}^{L_{f} - z} \{F_{k}(L_{f} - L_{0}) - F_{k}(L_{f} - L_{0})\} \, dz$$

Note that $P_{k}^{t}$ for $k = 1$ is given by

$$P_{1}^{t} = P\{L_{0} \leq Z(t_{1}) < L_{f} \mid L_{0} < Z(t_{0}) = L_{0}\} = \{F_{1}(L_{f} - L_{0}) - F_{k}(L_{f} - L_{0})\}$$

3. Maintenance model

3.1. CBM policy

CBM Policy has two limits - i.e. (i) the safe limit ($L_{p}$) and (ii) the critical limit ($L_{f}$) shown in Figure 2. The product is periodically inspected at time $jT$ where $k = 1, 2, \ldots, k$ where $k = T/\tau$. The maintenance decision at $jT$ is made using the following rules.

i. If the deterioration level at $t_{j}$, $Z(t_{j})$, is greater than a predetermined threshold $L_{f}$ (i.e. $Z(t_{j}) \geq L_{f}$) then the product fails. Note that the product is still functioning even if $Z(t_{j}) \geq L_{f}$ (in the failed state), and this reduces the production rate of the product. As soon as the failed state is detected, then CM action is done. After CM the state is restored to $Z_{0} = L_{0}$ (or the state at time $t_{0}$) (See Figure 2). The lessee incurs the cost $C_{0}$ due to the decrease in the production rate during $d$ unit of time - i.e. using
the product in failed state. We assume that \( d \) is a random variable with distribution function \( G(d) \) (as in [14]).

ii. \( I_{tr} \leq Z(\tau) < L_{tr} \), the product is preventively maintained. After PM the deterioration level is brought back to \( Z_0 \) (See Figure 2).

iii. \( I_{tr} < L_{tr} \leq Z(\tau) \), then do nothing (See Figure 2).

Figure 2 depicts a deterioration level at an inspection point, \( k = 1, 2, \ldots \) and the maintenance decision (PM, CM or Do Nothing) – which is based on the deterioration level and follows the rules (i)-(iii).

4. Total cost

A total cost to the lessor consists of Inspection cost, PM cost, CM cost, and Cost of production loss, and is given by

\[
TC(t, L_p; L) = C_{p}N_p(t, L_p; L) + \sum_{j=1}^{N_p(t, L_p; L)} C_p + C_{c}N_c(t, L_p; L) + C_{c}dN_c(t, L_p; L)d
\]  

(10)

The expected total cost is:

Expected Total cost = Expected Inspection cost + Expected PM cost + Expected CM cost + Expected Penalty Cost.

We obtain these costs as follows.

Expected of PM cost:

The expected of PM cost is the PM cost \( (C_p) \) multiplied by the number of PM in \((0, L)\) and it is given by

\[
E\left[ \sum_{j=1}^{N_p(t, L_p; L)} C_p \right] = E[N_p(t, L_p; L)]C_p
\]

where \( N_p(t, L_p; L) \) and \( C_p \) represent the number PM during the lease contract period \((L)\) and the PM cost at \( \tau \), respectively. The expected number of PM, \( E[N_p(t, L_p; L)] \) is given by

\[
E[N_p(t, L_p; L)] = \sum_{j=1}^{k} P^j_{tr}
\]

where \( k \) is the number of inspections in \((0, L)\) and \( P^j_{tr} \) is given in (9).

Expected of CM cost:

The expected of CM cost is the cost of each CM \( (C_c) \) multiplied by the expected number of failures, \( E[N_c(t, L_p; L)] \) in \((0, L)\) and it is given by

\[
E\left[ \sum_{j=1}^{N_c(t, L_p; L)} C_c \right] = E[N_c(t, L_p; L)]C_c,
\]

where the expected number of CM is given by

\[
E[N_c(t, L_p; L)] = \sum_{j=1}^{k} P^j_{tr}
\]

with \( P^j_{tr} \) given in (7).

Expected of Penalty Cost:

When the system fails at \( tr, Z(\tau) > L_{tr} \), it is considered that it is still functioning. The failed state only influences the performance of the product in the sense that the production rate is below the standard. Let \( d_0 \) denote the time required for fixing the failed product at period \( k \). As the lessor promises a high level of performance, then the downtimes is set at most \( d(d_0) \) is the maximum allowable downtime). If the downtime exceeded, the lessor incurs some penalty costs. As a result, the expected penalty cost is given by

\[
\text{Expected Penalty cost} = C_pE[N_c(t, L_p; L)]E[\text{Max}\{0, d_0 - d\}]
\]

where \( C_p \) is a penalty cost per unit time and \( E[\text{Max}\{0, d_0 - d\}] = \int_{\text{Max}\{0, d_0 - d\}} G(d) \).

As result, we have the expected total cost given in (11).

\[
ETC(t, L_p; L) = C_pE[N_c(t, L_p; L)] + E[N_p(t, L_p; L)]C_p + C_pE[N_c(t, L_p; L)] + C_cE[N_c(t, L_p; L)]E[\text{Max}\{0, d_0 - d\}]
\]  

(11)

4.1. Optimization of maintenance policy

As we study a lease contract from the viewpoint of a lessor, then the relevant measure is the expected total cost given in (11). The CBM policy studied is characterized by two parameters – i.e. an inspection interval \( (\tau) \) and a preventive maintenance threshold \((L_{tr})\). It is assumed that \( L_{tr} \) is provided by the OEM (original product manufacturer). Hence, we obtain
the optimal \( r \) for a fixed \( L_p \) such that to minimize the expected total cost. Since the Eq. (11) involves a complex integral equation, then a numerical approach will be applied to obtain the optimal value of \( r \).

5. Numerical examples

Suppose that the product under consideration is a reman dump truck leased for \( L \) months. Let \( f_{\alpha, \beta}(Z_t) \) be the pdf of Gamma process given in (3). The shape parameter \( (\alpha(t)) \) is given in (2) with \( \alpha = 0.3 \beta = 0.3 \) and \( \rho = 1.3 \). The other parameter values are as follows:

|\( \alpha \)\( \) | \( L_0 \) | \( L_p \) | \( L_f \) | \( C_i \) | \( C_p \) | \( C_C \) | \( C_d \) | \( L \) |
|---|---|---|---|---|---|---|---|---|
|300 | 0.0002 | 10 | 15 | 30 | 300 | 800 | 100 | 36 |

Note that \( L_0 \) was determined so that the reliability of the reman product equals 0.94 at the beginning of the lease period, and \( k = \lceil L / \tau \rceil \), where \( k \) takes integer values.

Results for the optimal \( \tau \) and the minimum expected total cost (ETC) with \( L = 36 \) (in months), \( \beta = 0.3 \), usage rate \( (u) \) is 500 (in km/day) and \( \alpha = 0.1 \). 3. 0.5 are shown in Table 1. Figure 3 shows that the optimal \( \tau \) is 9 months and the optimal ETC is \( 593.07 \).

We now describe the salient features of the numerical examples showing the influence of parameter values \( \alpha, \beta, \rho \) and usage rate of the dump truck to the optimal values of \( \tau \) and ETC as follows.

The effect of \( \alpha \): Large value of \( \alpha \) means that the deterioration rate is high, and this will accelerate the deterioration level of the truck. Hence, it needs to monitor the deterioration level more often in order to avoid failure. This agrees with the result shown in Table 1 that the inspection interval (\( \tau \)) decreases from 12 to 6 as \( \alpha \) increases from 0.1 to 0.3. This is as expected as the rate of deterioration is getting bigger. Furthermore, the increased in \( \alpha \) from 0.3 to 0.5 does significantly increase the deterioration rate and hence does not affect the optimal \( \tau \) (i.e. it still equals 6), but causes slightly the expected total cost to increase (from 795.82 to 899.06). This is due to the increase in CM and PM costs as the deterioration rate increases.

The effect of \( \beta \): \( \beta \) affects the deterioration growth rate, \( a_\mu (\tau_k - \tau_{k-1}) / \beta \) in reverse relationship which mean that the increased in \( \beta \) will decrease the deterioration rate. It can be seen through Tables 2 and 3 that when \( \beta \) increases from 0.4 to 0.5 with \( \alpha = 0.1 \), the optimal \( \tau \) increases from 9 to 12 (meaning that the product requires less frequent inspection). Other changes in \( \beta \) for \( \alpha \) varying from 0.1 to 0.3, only cause the ETC to decrease slightly. While for a given \( \alpha \), when \( \beta \) increases from 0.1 to 0.3, the optimal inspection interval decrease significantly from 12 to 6. Further increased in \( \beta \) (from 0.3 to 0.5) does not change the optimal inspection interval, but it does increase the ETC.

The effect of usage rate (\( u \)): We now examine the behaviour of the optimal solution when the usage rage varies. For a given values of \( \alpha, \beta \), and \( \rho \), the optimal inspection interval is nondecreasing when the usage rate increases (See Tables 4, 5, and 6). The optimal inspection interval decreases from 9 to 6 when the usage rate increases from 200 to 400, and the effect becomes very significant if \( \beta \) is getting larger – As shown in Table 6, for \( \beta = 0.5 \), the optimal interval reduces by 50% (i.e. from 12 to 6). This means that larger usage rate will require more inspection to be carried out to maintain the good condition of the dump truck.

The effect of \( \rho \) (severity of operating condition): For a given values of \( \alpha, \beta \), if \( \rho \) increases (meaning that the operating condition where product is used changes from a relatively flat contour land to high inclined contour land), the optimal inspection interval is non-decreasing. For instance, the optimal inspection interval decreases from 12 to 9 when \( \rho \) increases from 0.6 to 1.1 for \( \alpha = 0.1, \beta = 0.3 \) (see Tables 7 and 8).

In other words, more severe operating condition will cause a larger growth of the deterioration of the product, and this in turn needs more frequent inspection for monitoring the deterioration level.

5.1. Managerial implications

The reliability of a reman product is considered slightly below the reliability of a new product. Therefore, the reman product demands a more effective PM policy to ensure a high performance. CBM can detect failure before it occurs, and this in turn will reduce the number of failures and increase the availability of the product. The application of a CBM policy for the leased reman product will provide more values to a lessee (a customer) in term of the high availability. However, if the product is used with high usage and/or in a severe operating condition, the CBM policy implemented needs to be adjusted (or customised) – as the high usage pattern and/or a severe operating condition influence the rate of the degradation of the product. This in turn requires an appropriate inspection interval and increases total costs to maintain a good service. Consequently, the lessee’s usage pattern and the operating condition need to be considered by a lessor in pricing the LC.

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**Figure 3.** Plot of the expected total cost (ETC) vs. the inspection interval (\( \tau \)) for \( \beta = 0.3 \)

**Table 1.** The expected total cost for \( \beta = 0.3 \), usage rate \( (u) \) is 500 and \( \alpha = 0.1 \ 0.3 \ 0.5 \).

|\( \tau \) (months) | \( k \) | \( \alpha = 0.1 \) | \( \alpha = 0.3 \) | \( \alpha = 0.5 \) |
|---|---|---|---|---|
|1 | 36 | 1421 | 1464 | 1499 |
|2 | 24 | 985.749 | 976.809 | 1048 |
|3 | 12 | 731.344 | 850.606 | 942.031 |
|4 | 9 | 657.732 | 810.018 | 904.5 |
|6 | 6 | 501.91 | 795.817 | 899.055 |
|9 | 4 | 593.972 | 812.607 | 940.019 |
|12 | 3 | 609.81 | 860.069 | 932.335 |
|18 | 2 | 651.268 | 898.54 | 904.144 |

ETC, expected total cost.
We have studied a LC for a reman product where a CBM policy with periodic inspections is considered to minimize failures and unnecessary PMs, and therefore it improves the availability (which is of interest to the lessee) and yet decreases the total cost to the lessor. In this paper, the condition of the product is periodically monitored. One can consider the CBM in which the condition of the product is monitored continuously. Another interesting topic is to study the CBM where the inspection interval is not constant but it is dependent on the availability target.

### Table 2. The expected total cost for $\beta = 0.4$, usage rate ($u$) = 500 and $\alpha = 0.1$ to 0.5.

| $\tau$ (months) | $k$ | ETC ($) | $\alpha = 0.1$ | $\alpha = 0.3$ | $\alpha = 0.5$ |
|-----------------|-----|---------|----------------|----------------|----------------|
| 1               | 36  | 1372    | 1428           | 1452           |
| 2               | 24  | 840.361 | 925.01         | 982.919        |
| 3               | 12  | 669.538 | 788.058        | 874.655        |
| 4               | 9   | 589.609 | 742.491        | 842.158        |
| 6               | 6   | 521.907 | 731.939        | 823.748        |
| 9               | 4   | 498.537 | 745.394        | 883.052        |
| 12              | 3   | 505.626 | 778.024        | 920.612        |
| 18              | 2   | 651.268 | 898.54         | 904.144        |

ETC, expected total cost.

### Table 3. The expected total cost for $\beta = 0.5$, usage rate ($u$) = 500 and $\alpha = 0.1$ to 0.5.

| $\tau$ (months) | $k$ | ETC ($) | $\alpha = 0.1$ | $\alpha = 0.3$ | $\alpha = 0.5$ |
|-----------------|-----|---------|----------------|----------------|----------------|
| 1               | 36  | 1312    | 1407           | 1423           |
| 2               | 24  | 784.786 | 892.656        | 936.909        |
| 3               | 12  | 609.717 | 744.998        | 819.978        |
| 4               | 9   | 529.29  | 691.758        | 790.252        |
| 6               | 6   | 448.185 | 677.119        | 777.849        |
| 9               | 4   | 410.858 | 701.93         | 805.689        |
| 12              | 3   | 405.573 | 714.127        | 885.704        |
| 18              | 2   | 423.431 | 818.909        | 903.46         |

ETC, expected total cost.

### Table 4. The expected total cost for $\beta = 0.3$, $\alpha = 0.3$ and usage rate ($u$) = 200, ..., 500.

| $\tau$ (months) | $k$ | ETC ($) | $u = 200$ | $u = 400$ | $u = 500$ | $u = 600$ |
|-----------------|-----|---------|-----------|-----------|-----------|-----------|
| 1               | 36  | 1411    | 1464      | 1499      | 1478      |
| 2               | 24  | 883.591 | 976.859   | 1048      | 1066      |
| 3               | 12  | 717.219 | 850.606   | 942.031   | 890.777   |
| 4               | 9   | 641.5   | 810.018   | 904.5     | 854.655   |
| 6               | 6   | 581.341 | 795.817   | 899.055   | 837.956   |
| 9               | 4   | 566.591 | 812.607   | 940.019   | 875.89    |
| 12              | 3   | 578.974 | 860.069   | 932.335   | 912.136   |
| 18              | 2   | 616.985 | 898.54    | 904.144   | 903.839   |

ETC, expected total cost.

### Table 5. The expected total cost for $\beta = 0.4$, $\alpha = 0.3$ and usage rate ($u$) = 200, ..., 500.

| $\tau$ (months) | $k$ | ETC ($) | $u = 200$ | $u = 400$ | $u = 500$ | $u = 600$ |
|-----------------|-----|---------|-----------|-----------|-----------|-----------|
| 1               | 36  | 1352    | 1420      | 1428      | 1437      |
| 2               | 24  | 819.383 | 905.247   | 925.01    | 947.605   |
| 3               | 12  | 646.995 | 755.174   | 788.058   | 823.792   |
| 4               | 9   | 565.295 | 697.735   | 742.491   | 787.443   |
| 6               | 6   | 493.589 | 673.58    | 731.939   | 777.642   |
| 9               | 4   | 463.698 | 695.111   | 745.394   | 793.652   |
| 12              | 3   | 464.561 | 714.997   | 778.024   | 857.664   |
| 18              | 2   | 490.374 | 785.755   | 873.745   | 900.652   |

ETC, expected total cost.

### 6. Conclusions

We have studied a LC for a reman product where a CBM policy with periodic inspections is considered to minimize failures and unnecessary PMs, and therefore it improves the availability (which is of interest to the lessee) and yet decreases the total cost to the lessor. In this paper, the condition of the product is periodically monitored. One can consider the CBM in which the condition of the product is monitored continuously. Another interesting topic is to study the CBM where the inspection interval is not constant but it is dependent on the availability target.
required – in the sense that each interval is determined such that to meet at least the availability target.

**Declarations**

**Author contribution statement**

Hennie Husniah: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Udjianna S. Pasaribu: Analyzed and interpreted the data.

Rachmawati Wangsaputra: Contributed reagents, materials, analysis tools or data.

Bermawi P. Iskandar: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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**Data availability statement**

No data was used for the research described in the article.

**Declaration of interests statement**

The authors declare no conflict of interest.

**Additional information**

No additional information is available for this paper.

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**Table 6. The expected total cost for \( \beta = 0.5, \ a = 0.3 \) and usage rate \( (u) = 200,\ldots,500 \).**

| \( \tau \) (months) | \( k \) | \( \text{ETC} \) | \( u = 200 \) | \( u = 400 \) | \( u = 500 \) | \( u = 600 \) |
|-------------------|--------|-----------------|-------------|-------------|-------------|-------------|
| 1                 | 36     | 1293            | 1402        | 1407        | 1413        |
| 2                 | 24     | 756.57          | 878.89      | 892.656     | 909.226     |
| 3                 | 12     | 580.429         | 719.964     | 744.998     | 774.288     |
| 4                 | 9      | 494.744         | 654.705     | 691.758     | 732.633     |
| 6                 | 6      | 414.625         | 620.394     | 677.119     | 729.258     |
| 9                 | 4      | 371.875         | 642.415     | 701.93      | 735.868     |
| 12                | 3      | 360.712         | 671.449     | 714.127     | 780.949     |
| 18                | 2      | 367.64          | 710.094     | 818.909     | 885.864     |

ETC, expected total cost.

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**Table 7. The expected total cost for \( \beta = 0.3, \ \rho = 1.1 \), usage rate \( (u) = 500 \) and \( a = 0.1 \; 0.3 \; 0.5 \).**

| \( \tau \) (months) | \( k \) | \( \text{ETC} \) | \( a = 0.1 \) | \( a = 0.3 \) | \( a = 0.5 \) |
|-------------------|--------|-----------------|-------------|-------------|-------------|
| 1                 | 36     | 1410            | 1459        | 1490        |
| 2                 | 24     | 882.127         | 966.269     | 1031        |
| 3                 | 12     | 715.555         | 835.191     | 922.658     |
| 4                 | 9      | 639.623         | 791.586     | 886.392     |
| 6                 | 6      | 579.02          | 777.096     | 873.352     |
| 9                 | 4      | 563.646         | 790.64      | 920.557     |
| 12                | 3      | 575.538         | 831.26      | 928.711     |
| 18                | 2      | 613.067         | 890.528     | 904.131     |

ETC, expected total cost.

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**Table 8. The expected total cost for \( \beta = 0.3, \ \rho = 0.6 \), usage rate \( (u) = 500 \) and \( a = 0.1 \; 0.3 \; 0.5 \).**

| \( \tau \) (months) | \( k \) | \( \text{ETC} \) | \( a = 0.1 \) | \( a = 0.3 \) | \( a = 0.5 \) |
|-------------------|--------|-----------------|-------------|-------------|-------------|
| 1                 | 36     | 1360            | 1449        | 1472        |
| 2                 | 24     | 828.475         | 944.508     | 994.831     |
| 3                 | 12     | 657.068         | 802.148     | 875.946     |
| 4                 | 9      | 575.949         | 749.925     | 838.775     |
| 6                 | 6      | 504.417         | 728.901     | 822.912     |
| 9                 | 4      | 472.841         | 744.371     | 852.178     |
| 12                | 3      | 470.573         | 767.213     | 897.424     |
| 18                | 2      | 489.308         | 842.881     | 903.147     |

ETC, expected total cost.
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