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Overall Equipment Effectiveness Evaluation of Maintenance Strategies for Rented Equipment

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Abstract. Equipment performance is very important in the production process. Equipment performance can be determined by overall equipment effectiveness performance (OEE) and maintenance strategies. This study encourages the use of OEE, in addition to the estimated total maintenance costs, of rental equipment as a consideration in determining optimal maintenance strategies. Meanwhile, the proposed maintenance strategies are corrective maintenance (CM) and a combination of CM with preventive maintenance (PM). The aim of this study was to obtain a maintenance strategy that would minimize the estimated total maintenance costs and increase OEE. Mathematical models of estimated total maintenance costs are developed based on maintenance strategies generated by each maintenance combination. The results of this study showed that when a rental period increases by two years, a combination of CM and PM strategies will cause maintenance costs to increase by 37.54%. Meanwhile, if the lessor only does CM, the increase will be greater (i.e., 55.12%). Comparison of the two strategies revealed that the combination of PM with CM is more efficient than CM alone. Further, OEE experienced an average decline of 3.7% despite the maintenance strategy.

Keywords: Maintenance; OEE; Overall equipment effectiveness; Rent equipment

1. Introduction

At present, the manufacturing industry is facing rapid technological developments. Technology is generally expensive and requires special skills in both operating and maintaining it. This has resulted in a change in the industry paradigm. Generally, companies have their own equipment, so that production processes and maintenance activities can be carried out by the maintenance department within each company. However, companies with limited capital often choose to rent with maintenance of production equipment. Thus, companies can focus on their core business matters and improve efficiency by converting fixed costs to variable costs (Singgih et al., 2018). A company may rent out equipment (lessee) to other companies (lessors) with the cooperation stated in a contract agreement detailing the obligations of the lessor and the lessee. The lessor is generally obliged to maintain equipment performance, while the tenant is obliged to pay for the rented equipment. Thus, the lessor must devise maintenance strategies that can minimize total maintenance costs and optimize equipment performance so as not to exceed the budget

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based on lessee payments.

Some researchers have previously discussed rental equipment issues (Jaturonnatee, 2006; Pongpech and Murthy, 2006; Yeh and Chang, 2007; Yeh et al., 2009; Chang and Lo, 2011; Yeh and Kao, 2011; Schutz and Rezg, 2013; Zhou et al., 2015; Hajej et al., 2015; Mabrouk et al., 2016; Su and Wang, 2016; Hamidi et al., 2016; Zhou et al., 2016; Hung et al., 2017; Wang et al., 2018). Wang et al. (2018) and Hajej et al. (2015) focused on guarantees in the area of rental equipment. Other studies have addressed the issue of maintenance strategies by considering penalty factors in equipment rental transactions (Jaturonnatee, 2006; Pongpech and Murthy, 2006; Yeh and Chang, 2007; Yeh et al., 2009; Yeh and Kao, 2011; Yeh et al., 2011; Hung et al., 2017). They used equipment failure thresholds to determine the schedule and number of preventive maintenance (PM) imperfections that can minimize total maintenance costs. In addition to imperfect PMs, they used minimum CM to repair equipment failures. Generally, they consider penalties when equipment failures occur. However, penalties are not often considered for the duration of equipment repair. In fact, this often happens.

In contrast with Jaturonnatee et al. (2006), Pongpech and Murthy (2006) used a periodical PM scheme in which PM actions were implemented periodically with various levels of maintenance. Pongpech and Murthy (2006) extended a mathematical model to determine the ideal PM period and reduce the failure rate, resulting in a minimum estimated total maintenance charge. This research method was more practical, but the resulting performance was lower than that produced by Jaturonnatee et al. (2006). Yeh et al. (2009) expanded a mathematical model and algorithm to determine the total performed PM schedules, the time interval between PM actions, and the best efficiency level alongside the estimated total maintenance charge criteria. Yeh et al. (2009) considered decreases in the secure failure rate of each PM event during a rental period. However, Yeh et al. (2009) assumed that the time of each equipment repair would exceed the time specified in the contract agreement, and this does not always occur. Consequently, the lessor will be in an unfavorable condition.

In contrast with previous studies, Schutz and Rezg (2013) and Zhou et al. (2007, 2015) established a reliability threshold for determining PM schedules and discussed guarantees of rental equipment performance. Meanwhile, Mabrouk et al. (2016) used downtime as a barrier to determine when PM. Mabrouk et al. (2016) combined PM with imperfect CM as a maintenance strategy to determine future rental periods. Xiang et al. (2017) developed a multi-unit maintenance rental equipment scheme in which the effectiveness of the PM is determined to reduce the failure rate. One method used to determine PM effectiveness is the method of reducing the failure rate (FRRM) (Jaturonnatee, 2006; Pongpech and Murthy, 2006; Yeh and Chang, 2007). The FRRM reduces the equipment failure rate by a safe amount or a safe amount equal to the failure rates that exist after PM actions (Finkelstein, 2008). Another method for determining PM effectiveness is the age reduction method (ARM) (Zhou et al., 2007; Schutz and Rezg, 2013; Zhou et al., 2015; Hajej et al., 2015; Hamidi et al., 2016; Hung et al., 2017). The ARM is the age of the equipment returned earlier than today with a safe amount after PM actions (Finkelstein, 2008).

Out of the aforementioned research, only Zhou et al. (2015) and Schutz and Rezg (2013) discussed equipment performance as a result of maintenance activities. However, they did not discuss variable costs, such as penalties, in the context of optimization determination. According to his research, maintenance not only affects equipment performance but also affects the performance of maintenance activities; overall equipment effectiveness (OEE) can do both. OEE provides an overview of engine conditions determined by availability ratios, performance ratios, and quality ratios. These three ratios are important because they indicate the suitability of the equipment to be used in the production process (Pariaman et al., 2017; Rahman et al., 2018).

For this reason, the present research integrated both of them into rental equipment. In the present study, OEE was used as a measure of equipment performance. Meanwhile, the proposed maintenance strategies include minimal corrective maintenance (CM) and a combination of minimal CM with imperfect PM. ARM was also used in this study to determine the effectiveness of imperfect PM. The purpose of this study was to obtain a maintenance strategy that could minimize estimated total maintenance costs and increase OEE. Mathematical models of estimated total maintenance costs were developed based on maintenance strategies generated by each maintenance combination, and the failure rate was assumed to follow the Weibull distribution.

This article was arranged systematically as follows. Segment 2 illustrates the mathematical model developed in the present study. The characteristics of an optimal maintenance strategy are explored in Segment 3. Segment 4 presents the characteristics of the model through numerical analysis. Finally, Section 5 presents conclusions drawn from the previous exposure.

In this study, we recall various notations:

Table 1 Notations of the present model

Notations	Descriptions	Notations	Descriptions
L	Rent period	t	Time to act, imperfect PM
T	Preventive maintenance period	t_i	The i-th time for imperfect PM
δ	Maintenance level	t_i^*	The i-th time for optimal imperfect PM
δ^*	Maintenance level, optimal	$f(t)$	Failure rate
τ	Repair time	$F(t)$	Cumulative distribution function
C_f	Fixed charge, preventive maintenance	P	Probability of a delay in repair time
C_v	Variable charge, preventive maintenance	ω	Total equipment failures
n	Number of imperfect PM	$G(\tau)$	Cumulative distribution function for Tm
n^*	Number of imperfect PM, optimal	Tm	Duration of a random
C_r	Charge of repairs	α	Shape parameter
C_n	Charge of a penalty for failure	β	Scale parameter
C_τ	Charge of a late penalty	C_0	Estimated total maintenance costs without imperfect PM
C	Estimated total maintenance costs	$\Delta\%$	Efficiency rate
C^*	Estimated total maintenance charge, optimal	C_{cm}	Estimated total cost of minimal CM
C_{pm}	Estimated total cost of imperfect PM		

2. Methods

2.1 Mathematics Formulation

2.1.1. The estimated total cost of minimal CM

As found by Yeh et al. (2009), the present study showed an increase in failure rate ($f(t)$) based on the time function t with $f(0) = 0$. The lessor performs the minimum CM at the cost of C_r. The minimal CM aims to return the equipment to its original operating condition. The lessor receives a penalty in the case of a C_n failure. Additionally, the lessor receives an additional penalty if the duration of the repair exceeds the agreement. It was assumed that this event requires the duration of a random Tm improvement following the cumulative distribution function $G(\tau) = 1 - exp\left[-\left(\frac{\tau}{\vartheta}\right)^m\right]$ and probability P. Therefore, the estimated total cost minimal CM (C_{cm}) is calculated as follows:

$$C_r + C_n + PC_\tau \int_\tau^\infty G(t)\,dt \tag{1}$$

2.1.2. The estimated total cost of imperfect PM

The lessor reduces total failure with imperfect PMs during the rental period. After taking PM measures on t_i, the failure rate decreases at a fixed amount $\delta \geq 0$, where $0 < t_1 < t_2 < \ldots < Tn < L$. In this system, PM costs are non-negative and non-decreasing from the maintenance level $\delta \geq 0$. The estimated total cost of imperfect PM ($C_{pm}(\delta)$) is assumed to increase linearly according to the maintenance level δ. The estimated total cost of imperfect PM consists of fixed costs (C_f) and variable costs (C_v), so that the estimated total cost of imperfect PM ($C_{pm}(\delta)$) is calculated as follows:

$$C_{pm}(\delta) = C_f + C_v\,\delta, \text{where } C_f > 0 \text{ and } C_v \geq 0 \tag{2}$$

In this study, it is assumed that the duration of PM is so small as to be negligible, and thus it is assumed that equipment failures are corrected immediately.

2.1.3. The estimated number of failures

Similarly, Yeh et al. (2009) and Krit and Rebai (2013) stated that the failure rate follows the non-homogeneous Poisson process (NHPP) with an intensity of $f(t)$. The estimated number of failures (ω) is:

$$\omega = \omega(n, \delta, t) = \sum_{i=0}^{n} \int_{t_i}^{t_{i+1}} [f(t) - i\delta]dt = F(L) - \delta \sum_{i=1}^{n} (L - t_i) \tag{3}$$

where $t = (t_1, t_2, \ldots, t_n)$ is a route from time to time to act, imperfect PM.

2.1.4. Estimated total maintenance costs

Based on Equations 1, 2, and 3, the estimated total maintenance charge becomes:

$$C(n, \delta, t) = C_{cm}\omega + nCpm(\delta)$$

$$C(n, \delta, t) = \left[Cm + Cn + PC\tau \int_\tau^\infty G(\tau)\right]\omega + nCpm(\delta)$$

$$= C_{cm}F(L) + nCpm(\delta) - C_{cm}\delta \sum_{i=1}^{n} (L - T_i) \tag{4}$$

Deprived of PM action ($n = 0$), the estimated total maintenance charge decreases to:

$$C_0 \equiv C\big(0, 0, \underline{t}; L\big) = C_{cm}F(L) \tag{5}$$

The aim of this model is to discover the optimal PM strategy (n^*, δ^*, t^*) for the lessor so that the estimated total maintenance cost of Equation 4 is minimalized. Note that there are $n + 2$ choice variables (plus the total PM activities n, maintenance level δ, and periods t_i) in the purpose function Equation 4.

2.1.4. Overall equipment effectiveness (OEE)

Furthermore, OEE is used to determine equipment performance with the following equation (Supriatna et al., 2017; Supriatna et al.,2018):

$$OEE = \left\{\left(\frac{loading\ time - down\ time}{loading\ time}\right) x \left(\frac{TCT\ x\ PA}{OT}\right) x \left(1 - \frac{Process\ time}{loading\ time - down\ time}\right)\right\} \tag{6}$$

where TCT = theory of cycle time, PA = process amount dan, OT = operation Time.

The loading time was assumed to be rented periodically because the equipment should be suitable for use during that period. However, in practice, the availability time is reduced by the occurrence of downtime due to equipment failure. Therefore, Equation 6 was rewritten as follows:

$$OEE = \left\{\left(\frac{L-\omega\tau}{L}\right) x \left(\frac{TCT\ x\ PA}{OT}\right) x \left(1 - \frac{Process\ time}{L-\omega\tau}\right)\right\} \tag{7}$$

2.2. Optimal Policy

According to Equation 4, there is a trade-off between the estimated total cost of imperfect PM and the level of maintenance for some imperfect PM periods. Specifically, if the optimal number of imperfect PM activity is 0, then imperfect PM becomes invalid. This condition applies $C_0 = C_{cm}F(L)$ and vice versa. Therefore, Equation 4 can be derived as follows:

$$\text{Minimize } C(n, \delta, \underline{t}) = C_0 + nCpm(\delta) - C_{cm}\delta \textstyle\sum_{i=1}^{n}(L - t_i), \text{subject to}$$

$$f(t_i) - i\delta \geq 0, \text{for } i = 1, 2, 3, \ldots, n \tag{8}$$

Theorem 1. If the failure rate $(f(t))$ is a function that increases from t, then the optimal imperfect period (t_i^*) will equal the inverse of the failure rate $f^{-1}(i\delta)$ with the conditions $n > 0$ and $\delta > 0$. Thus, the optimal time to carry out PM i is when $f(t_i) = i\delta$ with $t_i^* = f^{-1}(i\delta)$, which shows that the failure rate decreases after an imperfect PM is performed. Then, Equation 8 becomes:

$$C(n, \delta | \underline{t}^*) = C_0 + nCpm(\delta) - C_{cm}\delta\{nL - \textstyle\sum_{i=1}^{n}[f^{-1}(i\delta)]\} \tag{9}$$

Theorem 2. Given any $n > 0$, the succeeding outcomes are as follows:

a) If the marginal variable cost of PM (C_v) is greater than $C_{cm}L$, then the optimal maintenance level for n is (δ_n^*) = 0.
b) If the variable cost of PM (C_v) is less than $C_{cm}L$, then the optimal maintenance level (δ_n^*) is between 0 and $f(t)/n$.

There exists a unique $\delta_n^* \in \left[0, \frac{f(L)}{n}\right]$ such that the estimated total charge is minimized.

The last judgment variable is used to determine the optimal total of PM activities in the rent period, which is in praxis the maximum $\bar{n}$ of total PM activities that can be completed within a finite rent period. We can specify $\bar{n} = \left[\frac{L}{\tau}\right]$ or a great total with its best value determined for n from 0 to $\bar{n}$. The following algorithm is used to determine the best strategies and PM $(n^*, \delta^*, \underline{t}^*)$ for the lessor.

1. If $b - KL \geq 0$, next $(n^*, \delta^*, \underline{t}^*)$ = (0, 0, 0) and end
2. Put $(n^*, \delta^*, \underline{t}^*) = (0, 0, 0), C(n^*, \delta^*, \underline{t}^*) = C_0, \bar{n} = \left[\frac{L}{\tau}\right]$ and $n = 1$
3. Search for $\delta_n^* \in \left[0, \frac{f(L)}{n}\right]$ such that $C(n, \delta_n^* | \underline{t}^*) = minC(n, \delta | \underline{t}^*)$
4. If $C(n, \delta_n^* | \underline{t}^*) < C(n^*, \delta^*, \underline{t}^*)$, next, put $C(n^*, \delta^*, \underline{t}^*) = C(n, \delta_n^* | \underline{t}^*)$ and $(n^*, \delta^*, \underline{t}^*) = (n^*, \delta_n^*, \underline{t}^*)$
5. If $n = \bar{n}$, count OEE then end; then, put $n = n + 1$ and go to Stage 3

The best level δ_n^* is the right solution to determine nonlinear search solutions using the Weibull distribution for a lifetime. This outcome would greatly improve the efficiency of the algorithm.

2.3. Weibull Case

As in a study by Yeh et al. (2009), who used two parameters for the Weibull distribution, the parameter scale $(\alpha) > 0$ and the parameter shape $(\beta) > 0$. The failure rate function of the Weibull distribution is $f(t) = \alpha\beta(\alpha t)^{\beta-1}$, then the failure rate increases in time t. It is implicit that the PM function charges $Cpm\,(\delta) = n(C_f + C_v\delta)$, which grows linearly with the maintenance level δ. Then, from Equation 8, mathematics programs become.

Minimize $C(n,\delta,\underline{t}) = C_{cm}(\alpha L)^{\beta} + \mathrm{n}(C_f + C_v\delta) - nC_{cm}\delta L + C_{cm}\delta\sum_{i=1}^{n} t_i$

subject to

$$f(t\_i\,) - i\delta \geq 0, \text{for } i = 1, 2, 3, \dots, n \tag{10}$$

and valid with assumed $n > 0$. The following outcomes apply for the Weibull case:

a) If the marginal variable cost of PM (C_v) is greater than $C_{cm}L$, then the optimal maintenance level to n is $\delta_n^* = 0$.
b) If the variable cost of PM (C_v) is less than $C_{cm}L$, then the optimal maintenance level is: $(\delta_n^*) = \left\{n\left(L-\frac{b}{K}\right)\left(\frac{1}{w}\right)\left(\frac{1}{\left(\sum_{i=1}^{n} i^{\frac{1}{\beta-1}}\right)}\right)\left(\frac{\beta-1}{\beta}\right)\right\}^{(\beta-1)}$

Additionally, the following algorithm was derived using the Weibull technique:

1. If $b - KL \geq 0$, next $(n^*,\ \delta^*,\ \underline{t}^*) = (0, 0, 0)$ and end, else put $n = 1$
2. Put $\delta_n^* = \left\{n\left(L-\frac{b}{K}\right)\left(\frac{1}{w}\right)\left(\frac{1}{\left(\sum_{i=1}^{n} i^{\frac{1}{\beta-1}}\right)}\right)\left(\frac{\beta-1}{\beta}\right)\right\}^{(\beta-1)}$ and $t_i^* = w(i\delta)^{\frac{1}{\beta-1}}$
3. If $n = \overline{n}$ count OEE, and end, else, put $n = n + 1$ and go to Stage 2

3. Results and Discussion

3.1. Numerical Examples

In the numerical analysis, the treatment strategy was carried out in two combinations:

1. The lessor only carries out minimal CM.
2. The lessor combines minimal CM with imperfect PM.

If the lessor only carries out minimal CM, then the estimated total maintenance costs adopt Equation 5. However, if the lessor combines both strategies, then the estimated total maintenance cost of care is to adopt Equation 4. The results of Equations 4 and 5 are used as a basis for calculating efficiency with the equation $\Delta\% = \left((C_0 - C^*)/C_0\right)100$.

If the minimal CM consists of repairs cost (C_r) = 100, penalties for equipment failure (C_n) = 200, and fines for the duration of repairs that exceed the agreement limit (C_τ) = 300, then according to Equation 1, the estimated total cost of minimal CM is $\left(C_{cm} = 100 + 200 + 300P\int_{\tau}^{\infty} G(t)\,dt\right)$ where random time (Tm) follows Weibull (2.0.5) and the duration of repairs (τ) is 1 and 2.

Imperfect PM costs consist of fixed costs (C_f) = 100 and variable costs (C_v) = 50. Adopting Equation 2, total imperfect PM costs are estimated as follows: (C_{cm}) = 100 + 50δ. Calculations from the model use Matlab. Table 2 recapitulates the results of the mathematical model with a combination of scale parameters (β) = 1.5 and 2, the leasing period (L) = 2, 4, and 6, duration of improvement (τ) = 1 and 2, and shape parameter (α) = 0.5 and 1. For samples, if the shape parameter (α) = 0.5, the scale parameter (β) = 1.5, the repair time (τ) = 1, the rent period (L) = 4, and the lessor only carries out minimal CM, then according to Equation 5, the estimated total maintenance cost (C_0) optimal is 1278.67. However, if the lessor performs minimal CM and imperfect PM, then according to Equation 4, the optimal estimated total maintenance cost (C^*) = 583.323 and the optimal maintenance level (δ^*) = 0.3819. In addition, an optimal number of imperfect PM (n^*) = 2 is obtained. This means that the lessor must perform imperfect PM twice during the rental period (i.e., when t_1 = 1.2672 and t_2 = 2.5334). Equipment performance is also obtained after imperfect PM with OEE = 95.2%. With the efficiency equation $\Delta\% = \left((C_0 - C^*)/C_0\right)100$, the lessor can do efficiency (Δ%)= 54.481%. That is, a combination of minimal CM with imperfect PM is more efficient than minimal CM alone. However, if the shape parameter (α) = 0.5, the scale parameter (β) = 1.5, the repair time limit (τ) = 2, the rental period (L) = 4, and the lessor only performs minimal CM, then the estimated total maintenance costs (C_0) = 1384.90. However, if the lessor combines it with imperfect PM, then the estimated optimal total maintenance cost (C^*) = 611.994 and the optimal maintenance level (δ^*) = 0.3823. The number of PM imperfects (n^*) = 2, and PM is done at t_1= 0.51972 and t_2 = 2.0789. After PM, OEE is 92.4%. The lessor can do efficiency (Δ%) = 55.81%.

Figure 1 shows the effects of scale parameters (β) and shape parameters (α) on the estimated optimal total maintenance costs. For example, if the scale parameter (β) = 1.5, the form parameter (α) = 0.5, and the rental period (L) = 2, then the estimated total maintenance cost (C_0) = 452.08 (if the lessor only performs minimal CM) and (C^*) = 312.420 (if the lessor performs minimal CM and imperfect PM). If the scale parameter (β) is increased from 1.5 to 2, then (C_0) = 452.08 (if the lessor only performs minimal CM) and (C^*) = 350.348 (if the lessor performs minimal CM and imperfect PM). However, if the scale parameter (β) and the rental period (L) do not change (1.5 and 2, respectively) and the scale parameter (α) increases from 0.5 to 1, then the estimated total maintenance cost is (C_0) = 1278.67 (if the lessor only performs minimal CM) or (C^*) = 621,241 (if the lessor performs minimal CM and imperfect PM). This means that increasing the scale and shape parameters will affect the estimated total maintenance costs. This shows that there was an increase in failure resulting in an increase in CM and the number of imperfect PM. In Figure 1, the blue line shows α = 0.5 and the red line shows α = 1.

Figure 2 shows a comparison between minimal CM and the combination of minimal CM with imperfect PM. According to Figure 2, the estimated total maintenance cost without PM is higher than that with both minimal CM and imperfect PM. As proof, if the scale parameter (β) = 1.5, the form parameter (α) = 0.5, and the rental period (L) = 2, then the maintenance strategy without PM or with only minimal CM has an estimated total maintenance cost (C_0) = 452.08. However, if the maintenance strategy is a combination of minimal CM and imperfect PM, then the estimated total maintenance cost (C^*) = 312.420, so that 30.893% is more efficient. If the rental period (L) is increased from 2 to 4, then the maintenance strategy without PM has an estimated total maintenance cost (C_0) = 1278.67. However, if the maintenance strategy is a combination of CM and PM, then it has an estimated total maintenance cost (C^*) = 583.323. This shows that imperfect PMs can reduce equipment failures, thus reducing repair and penalty costs. In Figures 1 and 2, the maintenance strategy without PM is plotted with the red line and the maintenance strategy with PM is plotted with the blue line.

Table 2 Number of receptors in each container

			τ = 1						τ = 2					
β	α	L	C_0	n^*	δ^*	C^*	Δ%	OEE	C_0	n^*	δ^*	C^*	Δ%	OEE
1.5	0.5	2	452.08	1	0.4209	312.420	30.893	0.950	489.64	1	0.4218	328.317	32.947	0.911
		4	1278.67	2	0.3819	583.323	54.381	0.952	1384.90	2	0.3823	611.994	55.810	0.924
		6	2349.07	3	0.3440	817.461	65.201	0.947	2544.22	3	0.3442	856.162	66.349	0.925
1.5	1	2	1278.67	2	0.7529	621.241	51.415	0.880	1384.90	1	1.1931	745.777	46.149	0.781
		4	3616.64	4	0.6237	1092.433	69.794	0.902	3917.09	2	1.0814	1365.294	65.145	0.829
		6	6644.18	6	0.5397	1496.844	77.471	0.906	7196.15	3	0.9736	1873.063	73.971	0.847
2	0.5	2	452.08	1	0.4724	350.348	22.503	0.950	489.64	1	0.4745	369.180	24.601	0.911
		4	1808.32	3	0.4862	826.043	54.320	0.940	1958.54	2	0.6497	918.664	53.095	0.902
		6	4068.71	5	0.4908	1301.967	68.001	0.931	4406.73	3	0.7372	1513.224	65.661	0.893
2	1	2	1808.32	2	1.2596	932.419	48.437	0.838	1958.54	1	1.8979	1176.719	39.919	0.707
		4	7233.27	4	1.5558	2162.230	70.107	0.829	7834.18	2	2.5986	3074.656	60.753	0.700
		6	16274.86	6	1.6827	3434.525	78.897	0.821	17626.90	3	2.9489	5152.896	70.767	0.693

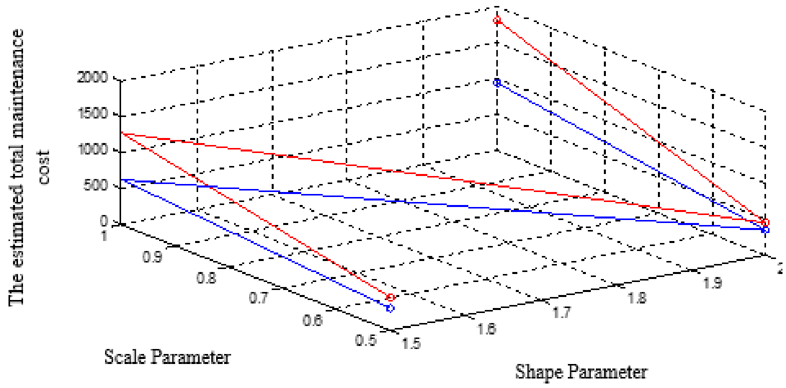

Figure 1 The effects of β and α on C^*

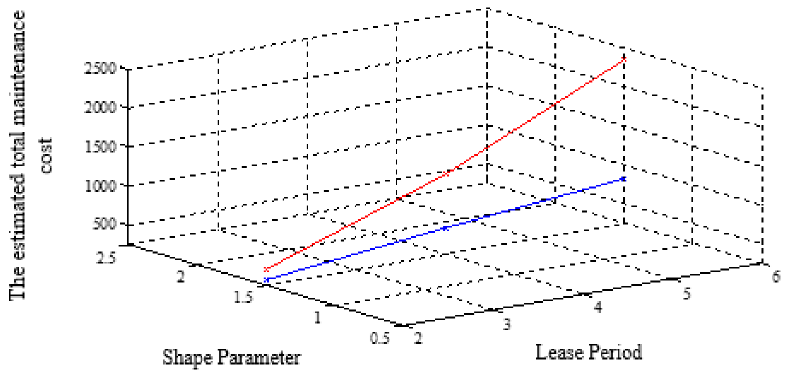

Figure 2 Comparison of maintenance strategies without PM and with PM

Figure 3 shows the relationship of maintenance degree (δ) with the estimated total maintenance charges (C) and OEE. When the maintenance degree and repair time increase, charges tend to rise as well. However, OEE does not necessarily increase because it is influenced by many factors, such as rent period, total PM, and amount of failure. In Figure 3, the repair time $\tau = 1$ is plotted with a red line, and $\tau = 2$ is plotted in blue.

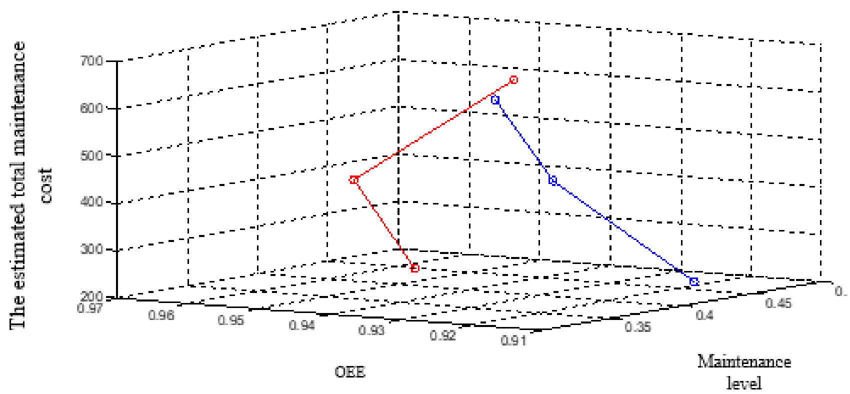

Figure 3 The relationship between δ with OEE and C

3.2. Discussion

The present article differs from others in that its parameters and variables are used not only to determine the estimated total maintenance costs but also to determine equipment performance (in this case, OEE). OEE can indicate sources that cause decreases in equipment performance, such as downtime and loss of speed. Downtime can be caused by equipment failure and can reduce the ratio of equipment availability to the production process, thus increasing estimated total maintenance costs. Therefore, equipment failure must be minimized. Meanwhile, loss of speed affects performance and quality levels. The duration of time needed for repairs is an indicator of low maintenance staff skills, inadequate maintenance methods, and incomplete infrastructure. This can serve as an evaluation of the lessor in carrying out maintenance to improve services to the lessee.

According to the numerical analytics found in the present study:
1. If the scale parameters (β) and shape parameters (α) increase, then the number of optimal imperfect PM (n^*) and the best maintenance level (δ^*) will increase.
2. If the rental period (L) increases, then the optimal estimated total maintenance cost (C^*), the number of optimal imperfect PM (n^*), and the percent decrease in cost ($\Delta\%$) will grow as well. This effect shows that PM activity has a large impact on estimated total maintenance costs when the rental period is relatively long.
3. If the level of maintenance (δ^*) increases, then equipment performance will increase.
4. If the duration of repairs (τ) increases, then the estimated total maintenance costs will increase.

4. Conclusions

The use of OEE for the purpose of renting equipment has been carried out successfully. The results of the OEE model characterization differed between different renting period conditions. OEE has a different value because it is influenced by many factors, such as renting period, number of PM, failure, repair time, and maintenance level. Using a rent period of two to six years and forming a shape parameter of 1.5 to 2, a scale parameter of 0.5 to 1, and a repair time from one to two hours results in an OEE of 69.3% to 95.0%. The use of PM and CM as a maintenance strategy yields differences in the estimated total maintenance charge by increasing scale parameters, shape parameters, rental periods, and the duration of repairs. Compared to the CM alone, the combination of PM and CM can improve efficiency from 30.893% to 78.897%. Thus, the results of this study can be considered by lessors to aid in devising maintenance strategies to maintain efficient equipment performance. The results of this study are promising for the future development of rented equipment studies using OEE. For the purposes of future research, OEE is now proven to measure equipment performance not only in the manufacturing industry but also in equipment rental. OEE is useful as a threshold to determine when PM should be executed. Future research may consider the duration of PM actions by generalizing various statistical distributions to devise maintenance strategies that can minimize total estimated maintenance charges.

References

Chang, W., Lo, H., 2011. Joint Determination of Lease Period and Preventive Maintenance Policy for Leased Equipment with Residual Value. *Computers & Industrial Engineering*, Volume 61(3), pp. 489–496

Finkelstein, M., 2008. *Failure Rate Modelling for Reliability and Risk*, Pham, H., (1st ed.), Springer London, New Jersey, United States

Hajej, Z., Rezg, N., Gharbi, A., 2015. A Decision Optimization Model for Leased Manufacturing Equipment with Warranty Under Forecasting Production/Maintenance Problem. *Hindawi*, Volume 2015, pp. 1–14

Hamidi, M., Liao, H., Szidarovszky, F., 2016. Non-cooperative and Cooperative Game-theoretic Models for Usage-based Lease Contracts. *European Journal of Operational Research*, Volume 255(1), pp. 163–174

Hung, W., Tsai, T., Chang, Y., 2017. Periodical Preventive Maintenance Contract for Leased Equipment with Random Failure Penalties. *Computers & Industrial Engineering*, Volume 113, pp. 437–444

Jaturonnatee, J.M.B., 2006. Optimal Preventive Maintenance of Leased Equipment with Corrective Minimal Repairs. *European Journal of Operational Research*, Volume 174, pp. 201–215

Krit, M., Rebai, A., 2013. Modeling of the Effect of Corrective and Preventive. *International Journal of Technology*, Volume 4(2), pp. 157–166

Mabrouk, A.B., Chelbi, A., Radhoui, M., 2016. Optimal Imperfect Maintenance Strategy for Leased Equipment. *International Journal of Production Economics*, Volume 178, pp. 57–64

Pariaman, H., Garniwa, I., Surjandari, I., Sugiarto, B., 2018. Performance Modelling for Maintenance Outsourcing Providers based on the Kano Model. *International Journal of Technology*, Volume 9(4), pp. 797–808

Pongpech, J., Murthy, D.N.P., 2006. Optimal Periodic Preventive Maintenance Policy for Leased Equipment. *Reliability Engineering and System Safety*, Volume 91(7), pp.772–777

Rahman, H.Z., Berawi, M.A., Susantono, B., Miraj, P., Petroceany, J.S., Maya, R., 2018. Investigation of an Operation and Maintenance Framework in the Railway Industry: A Case Study of the Makassar-Parepare. *International Journal of Technology*, Volume 9(3), pp. 549–557

Schutz, J., Rezg, N., 2013. Maintenance Strategy for Leased Equipment. *Computers & Industrial Engineering*, Volume 66(3), pp. 593–600

Singgih, M.L., Dalulia, P., Suef, M., Karningsih, P.D., 2018. Performance Modelling for Maintenance Outsourcing Providers based on the Kano Model. *International Journal of Technology*, Volume 9(4), pp. 797–808

Su, C., Wang, X., 2016. A Two-stage Preventive Maintenance Optimization Model Incorporating Two-dimensional Extended Warranty. *Reliability Engineering and System Safety*, Volume 155, pp. 169–178

Supriatna, A., Singgih, M.L., Widodo, E., Kurniati, N., 2017. Preventive Maintenance Considering OEE Threshold for Lease Equipment. *In:* Proceedings of the Asia Pacific Industrial Engineering & Management Systems Conference 2017, pp. 13–18

Wang, X., Li, L., Xie, M., 2018. Optimal Preventive Maintenance Strategy for Leased Equipment Under Successive Usage-based Contracts. *International Journal of Production Research*, Volume 57(18), pp. 5705–5724

Xiang, Y., Zhu, Z., Coit, D.W., Feng, Q., 2017. Condition-based Maintenance Under Performance-based Contracting. *Computers & Industrial Engineering*, Volume 111, pp. 391–402

Yeh, C., Lo, 2011. Optimal Length of Lease Period and Maintenance Policy for Leased Equipment with a Control-Limit on Age. *Mathematical and Computer Modeling,* Volume 54(9-10), pp. 2014–2019

Yeh, Kao, C., 2011. Preventive-Maintenance Policy for Leased Products Under Various Maintenance Costs. *Expert Systems with Applications,* Volume 38(4), pp. 3558–3562

Yeh, R.H., Chang, W.L., 2007. Optimal Threshold Value of Failure-rate for Leased Products with Preventive Maintenance Actions. *Mathematical and Computer Modelling*, Volume 46(5-6), pp. 730–737

Yeh, R.-H., Kao, K., Chang, W.-L., 2009. Optimal Preventive Maintenance Policy for Leased Equipment using Failure Rate Reduction. *Computers & Industrial Engineering*, Volume 57(1), pp. 304–309

Zhou, X., Li, Y., Xi, L., Lee, J., 2015. Multi-phase Preventive Maintenance Policy for Leased Equipment. *International Journal of Production Research*, Volume 53(15), pp. 37–41

Zhou, X., Wu, C., Li, Y., Xi, L., 2016. A Preventive Maintenance Model for Leased Equipment Subject to Internal Degradation and External Shock Damage. *Reliability Engineering and System Safety*, Volume 154, pp. 1–7

Zhou, X., Xi, L., Lee, J., 2007. Reliability-centered Predictive Maintenance Scheduling for a Continuously Monitored System Subject to Degradation. *Reliability Engineering and System Safety*, Volume 92(4), pp. 530–534