Analysis of Maintenance Service Contracts for Dump Trucks Used in Mining Industry with Simulation Approach

A Dymasius¹, R Wangsaputra¹ and B P Iskandar¹
¹Department of Industrial Engineering, Bandung Institute of Technology, Ganesha 10, Bandung, 40132, Indonesia

E-mail: andreas.dymasius@gmail.com

Abstract. A mining company needs high availability of dump trucks used to haul mining materials. As a result, an effective maintenance action is required to keep the dump trucks in a good condition and hence reducing failure and downtime of the dump trucks. To carry out maintenance in-house requires a high intensive maintenance facility and high skilled maintenance specialists. Often, outsourcing maintenance is an economic option for the company. An external agent takes a proactive action with offering some maintenance contract options to the owner. The decision problem for the owner is to decide the best option and for the agent is to determine the optimal price for each option offered. A non-cooperative game-theory is used to formulate the decision problems for the owner and the agent. We consider that failure pattern of each truck follows a non-homogeneous Poisson process (NHPP) and a queueing theory with multiple servers is used to estimate the downtime. As it involves high complexity to model downtime using a queueing theory, then in this paper we use a simulation method. Furthermore, we conduct experiment to seek for the best number of maintenance facilities (servers) which minimises maintenance and penalty costs incurred to the agent.

1. Introduction
A mining company uses heavy equipment (such as haul trucks, excavators, draglines) to load and haul mining materials. The heavy equipment play an important role for supporting the company’s business process. The equipment will undergo degradation with time and usage and ultimately leads to failure. According to Jack and Murthy [4], losses due to equipment can be very big e.g. in the mining industry reaches US $ 1 million per day. This data proves that the availability of such equipment is vital for business success in the mining industry. Therefore, it is necessary to conduct maintenance activities to maintain the condition of the equipment at a certain level of availability.

To keep the equipment in a high level of availability, it needs to carry out preventive maintenance (PM). If failure occurs then a corrective maintenance (CM) is done. PM and CM basically can be carried out by the owner of the equipment, but it needs maintenance facilities and trained personnel. In-house maintenance would not be economically viable due to a high annual maintenance costs. Therefore, outsourcing maintenance is of interest to the owner. Outsourcing can be interpreted as a delegation of business functions either partially or in whole to the other companies and implemented in the form of administrative and operational (Gomez, et.al. [1]). With the outsourcing policy, the owner should choose a maintenance contract option to guarantee a high availability at an affordable contract price, while OEM’s duty is to fulfill the availability target stated in a maintenance contract agreement. Figure 1 shows the operating diagram of the truck at a coal mining site.
In this study, the observed trucks are repairable and preventive maintenance is performed periodically. Any failure between PM will be minimally repaired. The failed truck is sent to maintenance service facilities for corrective maintenance. We consider that there are a limited number of service facilities (called servers) ($S$). The downtime of a truck is the sum of repair time and waiting time. If the downtime exceeds a target value then the penalty cost incurred the original equipment manufacturer, OEM (or agent). Workshop is managed by the OEM as a means to carry out the PM and CM activity. The decision problem for the owner is to select the maintenance contract option that maximizes its profit (or minimizes its total maintenance cost), and for the OEM is to determine optimal price for each maintenance option offered. This study uses a model of maintenance contracts formulated in Iskandar et al. [3] to obtain optimal decision for the owner and for the OEM. Several measures are required to get the total maintenance cost or total profit. The important measure is the expected downtime for each truck. In finding the expected downtime, it is impossible to obtain it using a queue formula with multiple servers (M/M/S/N) as the arrival of failed trucks follow a non-homogeneous Poisson process (NHPP) with intensity function $\lambda(t)$. As a result, a queueing process is not a Markovian process and then it involves high complexity to model downtime using a queueing theory. Alternatively, we use a simulation method to obtain the estimate for the expected downtime as suggested by Jackson and Pascual [5]. Also using simulation approach, we want to determine the optimal number of servers for the workshop so as to minimize the total of maintenance cost.

The paper is organised as follows. In section 2 we give model formulation for the service contract studied and simulation approach. Sections 3 deals with model analysis to find optimal decisions maximizing the expected profit for both OEM and the owner, and in Section 4 we carry out design of experiment to seek for the optimal number of servers. Finally, we present conclusion and a topic for further research in Section 5.
2. Model Formulation

We consider a maintenance contract model developed by Iskandar et al. [3] where three options are proposed in the maintenance contract. The following notations are used in the model formulation.

\(i\) : The i-th truck  
\(W\) : Deadline  
\(1/\lambda\) : Expected downtime for each failure  
\(P_{G_i}\) : Contract price for option 2 truck-i  
\(Y\) : Rate of use  
\(C_s\) : CM cost charged to owner or consumer  
\(C_p\) : Penalty cost per time unit  
\(\phi_y(O.)\) : Profit of owner  
\(\pi_y(O.)\) : Profit of OEM  
\(P_o\) : PM cost conducted in-house per period  
\(r_y(t), R_y(t)\) : Hazard function and cumulative hazard function corresponded to \(F(t, \alpha_y)\)  
\(F(t, \alpha_y)\) : Distribution of failure selected  
\(C_{pm}\) : Preventive Maintenance cost per time unit  
\(C_m\) : Corrective maintenance cost by OEM  
\(\tau\) : Contract period  
\(K\) : Profit  
\(C_b\) : Truck fixed costs during the contract period  
\(\lambda\) : Mean repairing time  
\(C_0\) : Setup cost for server  
\(C_1\) : Operational cost of server  
\(N\) : Amount of trucks  
\(E_{P_i}\) : Expected penalty cost for truck-i  
\(AVA_i\) : Actual availability of truck-i  
\(AVT\) : Availability targets  
\(PR\) : Penalty rate

The penalty cost is considered in the model considered. In calculating the penalty cost, the value of availability is necessary. If the value of the availability of the current system is below the promised performance by the OEM, the OEM is obliged to pay a penalty to the owner. We describe the penalty cost as follows.

2.1 Expected Downtime and Penalty Cost

CM is always minimal repair and hence CM does not affect the truck’s failure rate. As a result, failure process of the truck follows a NHPP. The intensity function of the failure process is obtained using the distribution of the first failure of a truck. We consider that the owner operates N trucks. Weibull distribution is considered as in Nahas et al. [9]. In this study, a correlation test was conducted to see whether there is an effect of useful life to the failure rate. Using a cox regression model, the effect of useful life can be measured as a covariate and the age of the truck as a baseline of hazard function according to a research by Lawless [6]. Using the cox regression model, the result shows that there is a significant effect of useful life to the calendar age but the effect is so small \((6 \times 10^{-6})\) so it can be said that the baseline hazard function is unchanged.

In calculating the expected penalty cost, Iskandar et al. [3] uses a queuing formula with N servers - M/M/S/N. As the arrival rate is non-Markovian, then we need to make a simplification using equation (1) (see Fig.2). As a result, we have a Homogeneous Poisson Process with intensity function \(\lambda\).

\[
\hat{\lambda} = \frac{\int_0^t h(x)dx}{t}
\]  

\(h(x)\) is the hazard rate function of the failure. As a result, the expected penalty rate can be calculated as: 

\[
E_{P_i} = \int_0^\infty P_1 \frac{h(x)dx}{t}
\]
Figure 2. Approximation of NHPP Arrival Rate with HPP Arrival Rate

Analytical Model:
Now, we obtain the total downtime. Using the queueing formula M/M/S/N, the expected of downtime (sum of waiting time and repair time) is described as follows. It is assumed that the failed truck is repaired with FCFS queuing system (first come first serve). We also need the following assumption to get the expression of the expected of downtime.

- The value of \( \tau \) (contract period) is large enough in compare to mean time between failures so we can apply steady state condition for the distribution of \( X_{ji} \).
- The mean total waiting and repair time is very small in compare to the mean time to failure or \( E(X_{ji}) \ll E(T_{ji}) = \frac{1}{\lambda} \) where \( \lambda \) is failure rate. As a result, the total downtime for given \( y \) for each truck is small compare with \( (W_y + \tau) \), hence

\[
K \left[ \sum_{i=1}^{z_j} T_{ji} + \tilde{T}_j - \sum_{i=1}^{z_j} X_{ji} \right] \approx K \left[ \sum_{i=1}^{z_j} T_{ji} + \tilde{T}_j \right] \approx K(W_y + \tau); Z_j, 1 \leq j \leq N
\]

(2)

Arrival rate (failure rate) of each truck and its service rate will be given by equation below:

\[
\lambda_k = \begin{cases} (N - K)\lambda, & 0 \leq K \leq N \\ 0, & K > N \end{cases}
\]

(3)

\[
\mu_k = \begin{cases} k\mu, & 0 \leq k \leq S \\ S\mu, & k > S \end{cases}
\]

(4)

If \( X_{ji} \) the total repair and waiting times with density function \( g(x) \) then according to Murthy and Asgharizadeh [8], the function is steady state for \( X_{ji} \) given by

\[
g(x) = e^{-\mu y} \sum_{k=0}^{S-1} \tilde{p}_k
\]

\[
+ \sum_{k=1}^{N-S} \tilde{p}_{k+S}(s\mu)^k \left[ \frac{e^{-\mu y} / (S\mu - \mu)k}{(k-j)! (S\mu - \mu)^j} \right]
\]

(5)

Where \( \tilde{P}_k, P_k, \) and \( P_0 \) \( k = 1, 2, ..., N - 1 \) is given by
\[
P_k = \begin{cases} 
\frac{(\lambda/\mu)^k}{k!} \frac{N^k}{(N-k)!} P_0, & k = 0, \ldots, S - 1 \\
\frac{(\lambda/S \mu)^k S^k}{(N-k)!} \frac{N^k}{S!} P_0, & k = S, S + 1, \ldots, N \\
0, & k > N 
\end{cases}
\]

\[
P_0 = \left[ \sum_{s=0}^{s-1} \frac{\lambda}{\mu^k} \left( \frac{N!}{(N-k)!} \right) + \sum_{s=0}^{s-1} \frac{S^s}{S!} \left( \frac{N!}{(N-k)!} \right) \right]^{-1} \tag{6}
\]

Then, the expected value of \( X_{ji} \) is given by

\[
E[X_{ji}] = \frac{1}{\mu} + \sum_{k=S}^{N-1} P_k (k - S + 1)/S \mu \tag{7}
\]

We will compare the average of downtime obtained from simulation with that of the queueing formula given in (7).

**Simulation Model:**
The simulation model will be developed using Promodel 4.2 where the number of trucks operated is 17 units. The service rate of the workshop is exponentially distributed. A flowchart of the simulation approach is given in Fig.4.

**Simulation of Failure Process:**
Because of the limitations of Promodel 4.2 in generating the arrival process with NHPP, then we use an algorithm developed by Lewis and Shedler [7]. The method is called "thinning algorithm" and can be used to generate random variates following NHPP. The algorithm is as follows.

1. Set the value \( t_0 = 0 \).
2. Set the value \( t = t_{i-1} \).
3. Generate value \( U_1 \) dan \( U_2 \), the uniform distribution with a range between 0 and 1.
4. Set \( t_i = t_{i-1} - \left( \frac{1}{\lambda^*} \right) \ln(U_1) \)
5. If the value of \( U_2 \leq \frac{\lambda(t^*)}{\lambda^*} \) then set \( t_i = t \). Otherwise, if the requirement is not met, then repeat step 3.

To ensure that the random variates generated through thinning algorithm is a NHPP, we do a hypothesis test using the MIL-HDBK-189. The procedure of the test MIL-HDBK-189 is as follows.

1. Determine the initial hypothesis \( (H_0) \) and the alternative hypothesis \( (H_1) \). \( H_0 \) means the data is a HPP dan \( H_1 \) means rejecting \( H_0 \) so that the data is a NHPP.
2. Determine the level of significance (\( \alpha \)) and critical areas (chi-square) \( \chi^2(\alpha, v) \) with a value of degree of freedom of \( v \) where \( v = 2(n - 1) \).
3. Perform statistical test that calculates the value of \( \frac{2n}{\hat{\beta}} \) dan \( \hat{\beta} \) by the following equation.

\[
\hat{\beta} = \frac{n}{\sum_{i=1}^{n-1} \ln(t_{ni})} \tag{8}
\]

4. Reject the initial hypothesis, if

\[
\frac{2n}{\hat{\beta}} < \chi^2(1 - \frac{\alpha}{2}, v) \text{ or } \frac{2n}{\hat{\beta}} > \chi^2(\frac{\alpha}{2}, v) \tag{9}
\]
Figure 2. Flowchart of Simulation Model

The simulation is run for 180 days with 40 replications. Results for the average downtime obtained using simulation and the analytical model is given in Table 1. The difference is very small and hence it can be said that there is no significant difference between the use of simulation approach and the queueing formula M/M/S/N.
2.2 Problem Statement

Maintenance contract starts at the end of warranty. OEM offers several maintenance contract packages and wants to determine the optimal price of the maintenance contract. We consider a situation where OEM provides the PM and CM services over a period of time $\tau$ with a contract value $P_G$. In the contract, there is a target of availability to be met by the OEM. Therefore, in this study we will use a model formulation of the maintenance contract option 2 in Iskandar et al. [3]. In the option 2, Availability value is calculated from the total waiting time and repair time of each truck. If the value of availability is below the target, then the OEM will pay a penalty cost as compensation for the owner. This study will observe N trucks operating in a mining industry. It is assumed that the OEM has limited the capacity of the workshop so we need to determine the optimal number of servers in order to minimize the expected of the penalty cost as well as the OEM’s maintenance costs – including setup and operational workshops costs.

3. Model Analysis

The purpose is to help the owner and the OEM to find optimal decisions maximizing the expected profit of both parties. The formula of penalty costs ($EP_i$) is given by

$$EP_i = \begin{cases} (AVT - AVA_i)(PR)(\tau), & AVA_i < AVT \\ 0, & AVA_i \geq AVT \end{cases}$$

where AVT and $AVA_i$ is availability target and actual availability, and PR is penalty rate. The formulation of a penalty cost can be changed according to agreement between the OEM and the owner.

3.1 Owner Decision Problem

The expected profit is equal to the revenue obtained from the operation of the truck and penalty costs paid by OEMs minus the price of maintenance contract and the annual cost of the truck given by

$$E[\phi_y(O_2; P_G)] = N \left[ K \left( \tau - R^2_y(W, W + \tau) \frac{1}{\lambda} \right) - C_b \right] + \sum_{i=1}^{N} (EP_i - P_{Gi})$$

3.2 OEM Decision Problem

The expected profit is equal to the price of the maintenance contract that paid by consumers minus penalty costs, setup service facility costs, operating service facility costs, corrective maintenance costs and preventive maintenance costs, given by

$$E[\pi_y(O_2; P_G)] = \sum_{i=1}^{N} (P_{Gi} - EP_i) - N \left[ c_{pm} \tau + R^2_y(W, W + \tau)c_m \right] - C_1S^2 - C_0S$$

3.3 Optimization
By using the principle of Nash equilibrium, we obtain the optimal value of the contract as follows.

\[
P_{G_i}^* = \frac{1}{2} \left[ K \left( \tau - R^2_\gamma (W, W + \tau) \frac{1}{\lambda} \right) + 2 EP_1 (\tau) + C_{pm} \tau + C_m R^2_\gamma (W, W + \tau) \right. \\
\left. + \frac{C_0 S + C_1 S^2}{N} - C_b \right] \quad (13)
\]

Then, we can obtain the expected profit for OEM (and also for the owner) is given by (Iskandar et al. [3])

\[
E[\pi_y (O_2; P_0 \ast)] = \frac{N}{2} \left[ (K \left( \tau - R^2_\gamma (W, W + \tau) \frac{1}{\lambda} \right) - C_{pm} \tau - C_b - C_m R^2_\gamma (W, W + \tau) \right. \\
\left. - \frac{C_0 S + C_1 S^2}{N} \right] \quad (14)
\]

3.4 Numerical Example

In the numerical example, we will use \( \alpha = 0.471 \) and \( \beta = 2.945 \). Other parameters are as follows.

**Table 2. Parameters' Value**

| Notation | Description                          | Value     | Unit            |
|----------|--------------------------------------|-----------|-----------------|
| \( C_{pm} \) | Preventive Maintenance Cost | 21168000 | Rupiah/year     |
| \( C_m \)   | Corrective Maintenance Cost         | 938628    | Rupiah/CM       |
| \( W \)      | Period of Observation               | 1.5       | Year            |
| \( C_b \)   | Price of Truck                      | 98280000 | Rupiah/year     |
| \( C_1 \)   | Workshop Operating Cost             | 1000000  | Rupiah/month/server |
| \( K \)      | Revenue from Consumer for each Truck | 255528000 | Rupiah/year     |
| \( \tau \)   | Contract Period                      | 0.5       | Year            |
| \( C_0 \)   | Workshop Setup Cost                 | 6000000  | Rupiah/month/server |
| \( S \)      | Number of Servers                   | 8         | Servers         |
| \( N \)      | Number of Trucks                    | 17        | Trucks          |
| \( 1/\lambda \) | Service Rate                       | 0.000521 | Year/CM         |
| \( PR \)    | Penalty Rate                        | 320       | Rupiah/Hour Contract Period |

From (13) and (14) we get the contract price for each truck is IDR 81,747,058.82 and the profit for the OEM (or the owner) is IDR 880,000,000.00.

4. Design of Experiment

The purpose is to determine the factors that influence the performance of the workshop. We will use design of experiments with 2^n factorial design method.

4.1 Factor and Response
Three factors are considered to affect the performance of the queuing system – i.e. (i) the arrival rate of truck, (ii) the number of servers at workshop, and (iii) the service rate of workshop. We consider that each factor has two levels (see Table 3).

### Table 3. Factor Value of Design of Experiment

| Factor | Description | Low Level | High Level |
|--------|-------------|-----------|------------|
| A      | Arrival Rate | α: 0.471125, β: 2.94506 | α: 0.31408, β: 2.94506 |
| B      | Number of Server(s) | 2 | 8.0000 |
| C      | Service Rate | 0.18775 | 0.1252 |

Experiments are conducted using Promodel 4.2 where the number of replication performed for each combination is 10 replication. Outputs from Promodel 4.2 are collected and processed by using analysis of variance (ANOVA).

#### 4.3 Analysis of Experiment Result

From design of experiment (DoE), we obtain that every factor exclude interaction between service rate and arrival rate, is significant factor. In this study, further investigation of the influence factors is focused on determining the optimal number of servers. Arrival rate and service rate can be affected by changing maintenance strategies CM and PM but determination is not incorporated into this study. Further experiments are conducted with the number of server 2, 4, 6, and 8, and the results are showed in Table 4.

### Table 4. Simulation Result of Several Number of Servers

| Replication | Number of Servers |
|-------------|-------------------|
|             | 2 | 4 | 6 | 8 |
| 1           | 11.72363 | 9.412059 | 9.34875 | 9.345858 |
| 2           | 12.37029 | 9.737966 | 9.692917 | 9.692917 |
| 3           | 12.0235  | 9.845931 | 9.814657 | 9.814657 |
| 4           | 11.39321 | 9.354828 | 9.268701 | 9.268701 |
| 5           | 11.57657 | 9.631299 | 9.606348 | 9.606348 |
| 6           | 10.5886  | 9.178015 | 9.149951 | 9.149951 |
| 7           | 12.09458 | 9.711495 | 9.64076  | 9.64076  |
| 8           | 11.71792 | 9.837377 | 9.793897 | 9.79277 |
| 9           | 11.30414 | 9.415907 | 9.361201 | 9.361201 |
| 10          | 12.85235 | 9.963775 | 9.879412 | 9.873627 |
| **Mean**    | 11.76448 | 9.608865 | 9.555659 | 9.554679 |

Based on the LSD test, the 6 and 8 servers does not differ significantly. In addition, the 4 and 6 servers does not differ significantly, but the 2 servers and 4 servers, and 2 and 6 servers are significantly different. It can be said that the optimal number of servers that minimizes the expected cost incurred by the OEM is 4 servers. Therefore, there will be cost saving maintenance cost and the penalty cost. With DoE, The new optimal value of contract is IDR 69,071,764.71 or 15.5% cheaper than that of the initial contract price. In addition, there is an increase in the expected profit for OEM and owner i.e. 5% from the initial expected profit (becomes IDR 928,600,000.00). Note that the initial contract value with 8 servers, is IDR 81,747,058.82 and the expected profit is IDR 880,000,000.00. Through the design of
experiments, the optimal number of servers will result in savings on the average value of the contract and increasing the expected profit.

5. Conclusion
This paper has studied a simulation approach to estimate the expected downtime for each truck, which is an important measure to obtain the actual availability of a truck. The study has shown that results obtained using simulation are very good estimates. In addition, using the design of the experiment we get the optimal number of servers (i.e. 4 servers) that gives a better result in term of cost saving and profit. In this study, we conducted simulation for a certain number of trucks. It is interesting to perform simulation for various number of trucks in order to find the optimal number of trucks used by a mining company, and this is one topic for further research.

6. References
[1] Gomez J F, Parra C, and Gonzalez V 2009 Outsourcing maintenance in service providers Taylor & Francis Group
[2] Harrel et al. 2004 Simulation using promodel 3rd ed. (New York: McGraw Hill)
[3] Iskandar et al. 2014 Maintenance service contracts for a fleet of dump trucks used in mining industry CIE44 & IMSS ‘14
[4] Jack N and Murthy D N P 2007 A new preventive maintenance strategy for items sold under warranty IMA Journal of Management Mathematics pp 121–129
[5] Jackson C and Pascual R 2007 Optimal maintenance service contract negotiation with aging equipment European Journal of Operational Research pp 387-398
[6] Lawless J F 2003 Statistical models and methods for lifetime data (New Jersey: John Wiley & Sons)
[7] Lewis P A W and Shedler G S 1979 Simulation of nonhomogeneous poisson processes by thinning Naval Research Logistics 26 pp 403–413
[8] Murthy D N P and Asgharizadeh E 1999 Optimal decision making in a maintenance service operation European Journal of Operational Research pp 259-273
[9] Nahas et al. 2008 Extended Great Deluge Algorithm for the Imperfect Preventive Maintenance Optimization of Multi-State Systems Reliability Engineering and System
[10] MIL-STD-882 1984 System Safety Program Requirement US Department of Defense
[11] Zhou et al. 2012 Preventive Maintenance Optimization for a Multi-Component System Under Changing Job Shop Schedule Reliability Engineering and System