Integrating Reliability Centered Maintenance with Statistical Forecasting Techniques and Cost Engineering on Machine in Casting Plant of Automotive Parts

Suthep Butdee and Tadpon Kullawong*

Department of Production Engineering, Faculty of Engineering, King Mongkut’s University of Technology North Bangkok, Bangkok, Thailand

* Corresponding author. E-mail: tadponk@yahoo.com

Received: 24 February 2015; Accepted: 7 April 2015; Published online: 28 April 2015

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Abstract
This paper describes the integration of reliability centered maintenance (RCM), Statistical Forecasting Techniques (SFT) and cost engineering to develop maintenance and cost management on Machine in Casting Plant of Automotive Parts. The main objective of RCM, SFT and cost engineering is the effective maintenance and cost management of the components of a machine inherent reliability value. Consequently, this research aims to manage the costs necessary to extend the service life of a machine through the use of probabilistic methods and simulation techniques in order to better identify the importance of every components in a machine with respect to maintenance costs. As a result of this research, our costing model allows to develop a methodology to determine maintenance costs which must be applied to some subsets of the elements of a machine, grouped according to their criticality and to identify the gap of costs between the true solution and the optimal maintenance interval.

Keywords: RCM, SFT, Cost engineering

1 Introduction

Cost engineering is the engineering practice devoted to the management of project cost, involving such activities as cost- and control- estimating, which is cost control and cost forecasting, investment appraisal, and risk analysis. Cost Engineers budget, plan and monitor investment projects. We seek the optimum balance between cost, quality and time requirements. Cost minimization has been always the traditional objective in maintenance planning; over the years, maintenance has been very often undervalued because of the strong business-oriented vision of firms managers who payed attention on production rather than on maintenance. Afterwards, the real advantages offered by the right application of maintenance techniques have been understood giving them the right collocation inside the firm management. The present paper shows a costing model to manage maintenance costs and improves it introducing simulation techniques to diversify the importance of the components of a plant by classifying their criticality with respect to maintenance costs.

Over the years, maintenance has been very often undervalued because of the strong business-oriented vision of firms managers who payed attention on production rather than on maintenance. Afterwards, the real advantages offered by the right application of maintenance techniques have been understood by reserving a branch of engineering to maintenance and by defining methodologies to manage it efficiently, among which RCM (Reliability Centered Maintenance).

RCM provides in fact an efficient and complete tool to improve maintenance policies involving service efficiency, plant reliability and budget and resources management. It allows to define maintenance plans of those activities which guarantee performances and
reliability in a component considering its importance and its mission in the production context. In fact, the maintenance services and time intervals are optimized considering the real criticality of the parts, guaranteeing their availability. Clearly, the implementation of a maintenance plan is not a trivial or a zero-cost operation and in this sense a cost analysis must be developed.

2 Literature Reviews

Cost minimization has been the traditional objective in maintenance planning. Deterministic models [1] on preventive maintenance optimization have established minima in costs based on operating cost parameters (repair, maintenance and acquisition). The use of deterministic methods, however, does not provide information about potential risk that results in nonoptimal maintenance planning for process plants [2]. Probabilistic models, on the other hand, use probability distributions to describe and represent natural variability and uncertainty in parameter, model and scenario [3]. Probabilistic models of scheduling preventive maintenance also minimize objective functions that reflect repair, replacement and preventive maintenance costs [4]. The preventive maintenance interval is optimized when the increasing rate of corrective maintenance costs (with respect to time) equals the decreasing rate of preventive maintenance costs.

In conducting this type of analysis, some important maintenance parameters must be considered: in general terms, it is possible to state that the main goal of a maintenance plan is to improve the availability of a production line. By defining up-time as the functioning time of the line and down-time as the off-duty time of the line due to a failure, the availability can be defined as the ratio between the up time and the sum of up-time and down-time. To improve this performance, one of the possible chance is to reduce the Mean Time Waiting for Spares (MTWS), i.e. the time necessary to wait for a spare when a substitution operation occurs.

The classical model dealing with the maintenance costs defines the management procedure by which the i-th component is substituted when it reaches a critical age; this time is defined, in the case of electromechanical components, by the number of utilization hours with respect to the service life, or life expectancy of its design. The substitution period, defined as $t_s$, is considered with respect to the last intervention of preventive or corrective maintenance independently. By defining ETTC ($t_c$) the average expected life for a component in the period $t_c$ as the equation (1).

$$ETTC(t_c) = \int_0^{t_c} R(x)dx$$  \hspace{1cm} (1)

Where $R(x)$ is the reliability function of the component.

The total cost between two maintenance interventions can be so evaluated as the sum of the cost related to a planned and to an unplanned intervention because of a failure of the component; each of those is weighted with its probability represented by the reliability and unreliability functions respectively. So, the total provisioning cost per time unit is the equation (2).

$$E(C_i) = \frac{E(C_{pi})R_i(t_c) + E(C_{ui})[1-R_i(t_c)]}{\int_0^\infty R(x)dx}$$  \hspace{1cm} (2)

where:

- $E(C_i)$ is the total expected cost of planned maintenance per time unit related to the i-th component;
- $E(C_{pi})$ is the expected cost of a planned and preventive intervention for the i-th component;
- $E(C_{ui})$ is the expected cost of an unplanned intervention due to a failure for the i-th component;
- $R_i(t)$ is the cumulative distribution function of the reliability of the i-th component.

By deriving the cost function with respect to $t_c$ time and setting to zero its first derivative, it is possible to evaluate the minimum of this equation (3) obtaining the optimal maintenance time which minimize the total costs:

$$\frac{d[E(C_i)]}{dt_c} = 0$$  \hspace{1cm} (3)

This work aims to generate a maintenance program that based on the RCM technique for the process-steam plant components. This technique should be able to minimize the downtime (DT) and improve the availability of the plant components. Also, it should benefits to decrease the spare parts
consumption system components. RCM is a systematic approach to determine the maintenance requirements of plant and equipment in its operating [5]. It is used to optimize preventive maintenance (PM) strategies. The developed PM programs minimize equipment failures and provide industrial plants with effective equipment [6]. RCM is one of the best known and most used devices to preserve the operational efficiency of the steam system. RCM operates by balancing the high corrective maintenance costs with the cost of programmed (preventive or predictive) policies, taking into account the potential shortening of “useful life” of the item considered. But it is difficult to select suitable maintenance strategy for each piece of equipment and each failure mode, for the great quantity of equipment and uncertain factors of maintenance strategy decision [7,8]. RCM philosophy employs preventive maintenance, predictive maintenance (PdM), real-time monitoring (RTM), run-to-failure (RTF) and proactive maintenance techniques is an integrated manner to increase the probability that a machine or component will function in the required manner over its design life cycle with a minimum of maintenance [9,10].

It is currently believed the application of probabilistic maintenance models to determine the optimal inspection rates considering the tradeoff between reliability and cost; accordingly, practical solutions can be obtained for the optimal inspection rates with the careful selection of appropriate probabilistic maintenance models [11]. In addition, the Weibull parameters are estimated using a new analytical method. Based on the model for optimizing maintenance policy for power equipment, the optimal number of overhauls and the optimal overhaul interval for minimizing the expected total maintenance cost are also analytically determined [12]. Several study cases were designed in order to test the proposed model, demonstrating its applicability and simplicity to determine an optimal maintenance policy [11,12].

On the recent basic of researches conducted in their better ways, Quantitative forecasting methods, including time series methods and causal econometric approaches, are used widely in industrial demand forecasting. Likewise, combining statistical and judgmental forecasts via a web-based tourism demand forecasting system resulted that this combination of quantitative and judgmental forecasts improves the overall forecasting accuracy [13]. Moreover, show that the proposed combination models can always provide desirable forecasting results compared to the existing traditional combination models [14]. In the same way, on many simulation results, a final combined approach that takes advantage of component forecasts should be better than the individuals, or at least equivalent to the best one, making it desirable to combine individuals to forecast wind-speed. Combined forecasting methodologies aggregate individual forecasting methods and take advantage of component models in order to improve the final forecasting performance [13,14].

3 Methodology

3.1 Our case study

This plant of foundry is capable of supplying top quality castings in a wide variety of alloyed cast irons, copper-based alloys, including aluminium bronzes and related alloys, as well as specially formulated aluminium alloys, for all types of glass moulds and machinery parts, all having material specifications equivalent to those originating from industrialized countries. All cast irons for glass moulds are chilled and annealed to the strictest quality standards to ensure the best possible glass production quality, and to maximize the life span of the moulds. The plant used main machines on electrical motors in Figure 1 about 100 units in manufacturing process in this plant in Figure 2.
3.2 **RCM steps**

The RCM steps are presented. The steps describe the systematic approach used to implement the preserves the system function, identifies failure mode, priorities failure used to implement the preserves the system function, identifies failure mode, priorities failure modes and performs PM tasks. The RCM steps are as follows [15]:

1. **Step 1:** system selection and data collection
2. **Step 2:** system boundary definition
3. **Step 3:** system description and functional block
4. **Step 4:** system function functional failures
5. **Step 5:** failure mode effect analysis
6. **Step 6:** logic tree diagram
7. **Step 7:** task selection.

3.3 **Criticality analysis**

Criticality analysis is a tool used to evaluate how equipment failures impact organizational performance in order to systematically rank plant assets for the purpose of work prioritization, material classification, PM development and reliability improvement initiatives [16]. In general, failure modes, effects and criticality analysis (FMEA/FMECA) required the identification of the following basic information in Table 1. Criticality of each machine (MC) was calculated based on the following four criteria:

1. Effect of the machine downtime on the production process (EM).
2. Utilization rate of the machine (Bottleneck or not) (UR).
4. Technical complexity of the machine and need of external maintenance resources (MTC).

<table>
<thead>
<tr>
<th>Part No.</th>
<th>Weight Machine Code</th>
<th>SEI</th>
<th>EM</th>
<th>UR</th>
<th>MCT</th>
<th>Criticality Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Motor &amp; Pump 1</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>26</td>
</tr>
<tr>
<td>2</td>
<td>Motor 2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>23</td>
</tr>
<tr>
<td>3</td>
<td>Motor 3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>26</td>
</tr>
</tbody>
</table>

Each of the criteria was given a weight showing its importance relative to the criticality indices. The weight of each criterion ranges from zero (no effect) to three (very important effect). Machine criticality was then calculated in the equation (4) and criticality codes such as A (most critical machine): 20 to 27, B: 12 to 19, C: 0 to 11.

\[
MC = 3*EM + 2*UR + 3*SEI + 1*MTC \quad (4)
\]

3.4 **Failure Mode Effects Analysis (FMEA)**

Failure modes and effects analysis (FMEA) is a step-by-step approach for identifying all possible failures in a design, a manufacturing or assembly process, or a product or service.

This is the severity rating, or S. Severity is usually rated on a scale from 1 to 10, where 1 is insignificant and 10 is catastrophic. If a failure mode has more than one effect, write on the FMEA table only the highest severity rating for that failure mode.

For each cause, determine the occurrence rating, or O. This rating estimates the probability of failure occurring for that reason during the lifetime of your scope. Occurrence is usually rated on a scale from 1 to 10, where 1 is extremely unlikely and 10 is inevitable. On the FMEA table, list the occurrence rating for each cause.

For each control, determine the detection rating, or D. This rating estimates how well the controls can detect either the cause or its failure mode after they have happened but before the customer is affected. Detection is usually rated on a scale from 1 to 10, where 1 means the control is absolutely certain to detect the problem and 10 means the control is certain not to detect the problem (or no control exists). On the FMEA table, list the detection rating for each cause.

The risk priority number, or RPN was then calculated in the equation (5).

\[
RPN = (S) \times (O) \times (D) \quad (5)
\]

Risk Evaluation such as Small Risk: RPN < 60, Medium Risk: RPN < 80 and High Risk: RPN < 100 and Crisis Risk: RPN > 100, then we should consider the RPN of components with the highest value first. Table 2 shows a sample of some valves of RPN.
On our case study, we selected the way to rate scores and to classify RPN as small, medium, high or crisis by Meetings and brainstorming of staff members such as Managers, Engineers, Chiefs, Technicians and Workers in Figure 3.

3.5 Maintenance Assessment of Reliability Engineering

We applied Maintenance Assessment of Reliability Engineering to calculate the probability on the parameters of reliability. To begin with, we don’t have the data of Time To Fail (TTF); therefore, we applied SFT on Non Linear Regression, to predict our machine’s life time and TTF by the machine data of vibration in Table 3.

Table 2: Sample of some values of RPN

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Motor &amp; Pump 1</td>
<td>Having more vibration &amp; higher temperature and unusual noise</td>
<td>Information</td>
<td>Scores</td>
<td>Information</td>
<td>Scores</td>
</tr>
<tr>
<td></td>
<td></td>
<td>It can not produce efficiently</td>
<td>6</td>
<td>Failure of bearing and gear</td>
<td>6</td>
<td>Temperature measurement, vibration analysis and unusual noise</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor stopped unexpectedly (burns)</td>
<td>6</td>
<td>Using electical overload</td>
<td>3</td>
<td>Daily monitoring</td>
</tr>
<tr>
<td>2</td>
<td>Motor 2</td>
<td>Having more vibration &amp; higher temperature and unusual noise</td>
<td>Information</td>
<td>Scores</td>
<td>Information</td>
<td>Scores</td>
</tr>
<tr>
<td></td>
<td></td>
<td>It can not produce efficiently</td>
<td>6</td>
<td>Failure of bearing and gear</td>
<td>6</td>
<td>Temperature measurement, vibration analysis and unusual noise</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor stopped unexpectedly (burns)</td>
<td>6</td>
<td>Using electical overload</td>
<td>3</td>
<td>Daily monitoring</td>
</tr>
<tr>
<td>3</td>
<td>Motor 3</td>
<td>Having more vibration &amp; higher temperature and unusual noise</td>
<td>Information</td>
<td>Scores</td>
<td>Information</td>
<td>Scores</td>
</tr>
<tr>
<td></td>
<td></td>
<td>It can not produce efficiently</td>
<td>6</td>
<td>Failure of bearing and gear</td>
<td>6</td>
<td>Temperature measurement, vibration analysis and unusual noise</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor stopped unexpectedly (burns)</td>
<td>6</td>
<td>Using electical overload</td>
<td>3</td>
<td>Daily monitoring</td>
</tr>
</tbody>
</table>

Figure 3: Our meetings and brainstorming of staff members to rate scores and to classify RPN.

Table 3: Sample of machine data of vibration

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Motor &amp; Pump 1</td>
<td>Motor 2</td>
<td>Motor 3</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Time (hours)</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>Vibration (mm/s)</td>
<td>Vibration (mm/s)</td>
<td>Vibration (mm/s)</td>
<td>Vibration (mm/s)</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>2.49</td>
<td>2.49</td>
<td>2.51</td>
</tr>
<tr>
<td>5</td>
<td>400</td>
<td>2.65</td>
<td>2.65</td>
<td>2.67</td>
</tr>
<tr>
<td>6</td>
<td>600</td>
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<td>2.87</td>
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<tr>
<td>7</td>
<td>800</td>
<td>2.81</td>
<td>2.81</td>
<td>2.95</td>
</tr>
<tr>
<td>8</td>
<td>1000</td>
<td>2.88</td>
<td>2.88</td>
<td>2.99</td>
</tr>
<tr>
<td>9</td>
<td>1200</td>
<td>2.88</td>
<td>2.88</td>
<td>3.12</td>
</tr>
<tr>
<td>10</td>
<td>1400</td>
<td>2.96</td>
<td>2.96</td>
<td>3.16</td>
</tr>
<tr>
<td>11</td>
<td>1600</td>
<td>3.12</td>
<td>3.12</td>
<td>3.31</td>
</tr>
<tr>
<td>12</td>
<td>1800</td>
<td>3.12</td>
<td>3.12</td>
<td>3.44</td>
</tr>
<tr>
<td>13</td>
<td>2000</td>
<td>3.22</td>
<td>3.22</td>
<td>3.55</td>
</tr>
<tr>
<td>14</td>
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<td>17</td>
<td>2800</td>
<td>3.36</td>
<td>3.36</td>
<td>3.81</td>
</tr>
<tr>
<td>18</td>
<td>3000</td>
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<td>3.98</td>
</tr>
<tr>
<td>19</td>
<td>3200</td>
<td>3.41</td>
<td>3.41</td>
<td>4.07</td>
</tr>
<tr>
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<td>3400</td>
<td>3.41</td>
<td>3.41</td>
<td>4.07</td>
</tr>
<tr>
<td>21</td>
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<tr>
<td>23</td>
<td>4000</td>
<td>3.41</td>
<td>3.41</td>
<td>4.07</td>
</tr>
<tr>
<td>24</td>
<td>4200</td>
<td>3.41</td>
<td>3.41</td>
<td>4.07</td>
</tr>
<tr>
<td>25</td>
<td>4400</td>
<td>3.41</td>
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<td>4.07</td>
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<td>4600</td>
<td>3.41</td>
<td>3.41</td>
<td>4.07</td>
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<td>27</td>
<td>4800</td>
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<td>3.41</td>
<td>4.07</td>
</tr>
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<td>28</td>
<td>5000</td>
<td>3.41</td>
<td>3.41</td>
<td>4.07</td>
</tr>
<tr>
<td>29</td>
<td>5200</td>
<td>3.41</td>
<td>3.41</td>
<td>4.07</td>
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<td>30</td>
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<td>3.41</td>
<td>4.07</td>
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<tr>
<td>33</td>
<td>6000</td>
<td>3.41</td>
<td>3.41</td>
<td>4.07</td>
</tr>
</tbody>
</table>
After that, we applied SFT on Decomposition Method in Non Linear Regression Analysis, to monitor vibration and to forecast vibration causes damage and TTF, by the machine data of vibration according to the standard of ISO 10816-3 in Figure 4. We used Statistical Software in Figure 5-7 to estimate the parameters and the equation in Table 4. So, we are able to forecast and to summarize the data of TTF in Table 5.

Figure 4: ISO 10816-3.

Figure 5: Decomposition Method in Non Linear Regression Analysis of Motor & Pump 1.

Figure 6: Decomposition Method in Non Linear Regression Analysis of Motor 2.

Figure 7: Decomposition Method in Non Linear Regression Analysis of Motor 3.
Table 4: Summary on Decomposition Method in Non Linear Regression Analysis

<table>
<thead>
<tr>
<th>No.</th>
<th>Machine Code</th>
<th>Durations (hours)</th>
<th>X: Time (200 hours)</th>
<th>Equations</th>
<th>Coefficient of Determination</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Motor &amp; Pump 1</td>
<td>2000 to 4800</td>
<td>1 to 15</td>
<td>Y = 2.48 + 0.07495 X - 0.001071 X²</td>
<td>97.1% 96.6%</td>
<td>To monitor vibration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5000 to 6000</td>
<td>1 to 6</td>
<td>Y = 3.3 + 0.1815 X - 0.1004 X² + 0.01667 X³</td>
<td>98.9% 97.2%</td>
<td>To forecast vibration causes damage</td>
</tr>
<tr>
<td>2</td>
<td>Motor 2</td>
<td>1000 to 4600</td>
<td>1 to 19</td>
<td>Y = 1.112 + 0.2512 X - 0.00695 X²</td>
<td>98.1% 97.9%</td>
<td>To monitor vibration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4800 to 5600</td>
<td>1 to 5</td>
<td>Y = 3.38 + 0.3143 X - 0.1582 X² + 0.0275 X³</td>
<td>99.8% 99.3%</td>
<td>To forecast vibration causes damage</td>
</tr>
<tr>
<td>3</td>
<td>Motor 3</td>
<td>1400 to 4000</td>
<td>1 to 14</td>
<td>Y = 1.616 + 0.2372 X - 0.0075 X²</td>
<td>96.7% 96.1%</td>
<td>To monitor vibration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4200 to 5200</td>
<td>1 to 6</td>
<td>Y = 3.357 + 0.284 X - 0.1006 X² + 0.01398 X³</td>
<td>99.6% 99.0%</td>
<td>To forecast vibration causes damage</td>
</tr>
</tbody>
</table>

Table 5: Summary of the data of Time To Fail: TTF (unit: hours)

<table>
<thead>
<tr>
<th>No.</th>
<th>Machine Code</th>
<th>Time To Failure: TTF (hours)</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Motor &amp; Pump 1</td>
<td>6800</td>
<td>13600</td>
</tr>
<tr>
<td>2</td>
<td>Motor 2</td>
<td>6300</td>
<td>12600</td>
</tr>
<tr>
<td>3</td>
<td>Motor 3</td>
<td>6100</td>
<td>12200</td>
</tr>
</tbody>
</table>

Therefore, we applied Excel Simulation to calculate the equation on Decomposition Method in Non Linear Regression Analysis such as Motor & Pump 1, Motor 2 and Motor 3 in Figure 8 to 10. After that, we adopted Reliability Engineering for the calculation by using graph probability (Probability Plotting) with Statistical Software in Figure 11-13 to estimate the parameters.

Table 6: Sample of the summarized results on Goodness of Fit

<table>
<thead>
<tr>
<th>No.</th>
<th>Machine Code</th>
<th>Parameters</th>
<th>K-S Test (α = 0.05, n)</th>
<th>Hypothesis test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Motor &amp; Pump 1</td>
<td>1.64093</td>
<td>23892.7</td>
<td>0.2239</td>
</tr>
<tr>
<td>2</td>
<td>Motor 2</td>
<td>1.64093</td>
<td>22135.9</td>
<td>0.2239</td>
</tr>
<tr>
<td>3</td>
<td>Motor 3</td>
<td>1.64093</td>
<td>21433.1</td>
<td>0.2239</td>
</tr>
</tbody>
</table>

In addition, we tested conditions about Goodness of Fit Test to confirm that a hypothesized distribution fits a data set by Kolmogorov–Smirnov Test for the small population using the equation (6)-(9). Then we created Excel Simulation to calculate the equation (6)-(9) in Figure 14 and the results on Goodness of Fit are summarized in Table 6.

Figure 8: Excel Simulation to calculate the equations on Decomposition Method in Non Linear Regression Analysis of Motor & Pump 1.
Figure 9: Excel Simulation to calculate the equations on Decomposition Method in Non Linear Regression Analysis of Motor 2.

Figure 10: Excel Simulation to calculate the equations on Decomposition Method in Non Linear Regression Analysis of Motor 3.

Figure 11: Probability Plotting with Statistical Software of Motor & Pump 1.

Figure 12: Probability Plotting with Statistical Software of Motor 2.
Statistical Hypothesis:

Test Statistics by Kolmogorov-Smirnov Test:

\[ d = \max \left[ \left| F(t_i) - \hat{F}(t_i) \right| \right] \]  

(6)

\[ F(t_i) = 1 - e^{-\frac{t_i}{\alpha}} \]  

(7)

\[ \hat{F}(t_i) = \text{Opportunity of Breakdown by Table 7} \]  

(8)

\[ d_{\alpha} = \text{Critical Values of Komogorov-Smirnov Tests by Table 8} \]  

(9)

Decision criteria on Significance level (\(\alpha\)): Accept \(H_0\) if \(d < d_{\alpha}\).

**Table 8: Critical Values of Komogorov-Smirnov Tests [17]**

<table>
<thead>
<tr>
<th>Sample Size</th>
<th>0.2</th>
<th>0.1</th>
<th>0.05</th>
<th>0.02</th>
<th>0.01</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.900</td>
<td>0.950</td>
<td>0.975</td>
<td>0.990</td>
<td>0.995</td>
</tr>
<tr>
<td>2</td>
<td>0.684</td>
<td>0.776</td>
<td>0.842</td>
<td>0.900</td>
<td>0.929</td>
</tr>
<tr>
<td>3</td>
<td>0.565</td>
<td>0.636</td>
<td>0.708</td>
<td>0.785</td>
<td>0.829</td>
</tr>
<tr>
<td>4</td>
<td>0.493</td>
<td>0.565</td>
<td>0.624</td>
<td>0.689</td>
<td>0.734</td>
</tr>
<tr>
<td>5</td>
<td>0.447</td>
<td>0.509</td>
<td>0.563</td>
<td>0.627</td>
<td>0.669</td>
</tr>
<tr>
<td>6</td>
<td>0.410</td>
<td>0.468</td>
<td>0.519</td>
<td>0.577</td>
<td>0.617</td>
</tr>
<tr>
<td>7</td>
<td>0.381</td>
<td>0.436</td>
<td>0.483</td>
<td>0.538</td>
<td>0.576</td>
</tr>
<tr>
<td>8</td>
<td>0.358</td>
<td>0.410</td>
<td>0.454</td>
<td>0.507</td>
<td>0.542</td>
</tr>
<tr>
<td>9</td>
<td>0.339</td>
<td>0.387</td>
<td>0.430</td>
<td>0.480</td>
<td>0.513</td>
</tr>
<tr>
<td>10</td>
<td>0.323</td>
<td>0.369</td>
<td>0.409</td>
<td>0.457</td>
<td>0.489</td>
</tr>
<tr>
<td>11</td>
<td>0.308</td>
<td>0.352</td>
<td>0.391</td>
<td>0.437</td>
<td>0.468</td>
</tr>
<tr>
<td>12</td>
<td>0.296</td>
<td>0.338</td>
<td>0.375</td>
<td>0.419</td>
<td>0.449</td>
</tr>
<tr>
<td>13</td>
<td>0.285</td>
<td>0.325</td>
<td>0.361</td>
<td>0.404</td>
<td>0.432</td>
</tr>
<tr>
<td>14</td>
<td>0.275</td>
<td>0.314</td>
<td>0.349</td>
<td>0.390</td>
<td>0.418</td>
</tr>
<tr>
<td>15</td>
<td>0.266</td>
<td>0.304</td>
<td>0.338</td>
<td>0.377</td>
<td>0.404</td>
</tr>
<tr>
<td>16</td>
<td>0.258</td>
<td>0.295</td>
<td>0.327</td>
<td>0.366</td>
<td>0.392</td>
</tr>
<tr>
<td>17</td>
<td>0.250</td>
<td>0.286</td>
<td>0.318</td>
<td>0.355</td>
<td>0.381</td>
</tr>
<tr>
<td>18</td>
<td>0.244</td>
<td>0.279</td>
<td>0.309</td>
<td>0.346</td>
<td>0.371</td>
</tr>
<tr>
<td>19</td>
<td>0.237</td>
<td>0.271</td>
<td>0.301</td>
<td>0.337</td>
<td>0.361</td>
</tr>
<tr>
<td>20</td>
<td>0.232</td>
<td>0.265</td>
<td>0.294</td>
<td>0.329</td>
<td>0.352</td>
</tr>
<tr>
<td>25</td>
<td>0.208</td>
<td>0.238</td>
<td>0.264</td>
<td>0.295</td>
<td>0.317</td>
</tr>
<tr>
<td>30</td>
<td>0.190</td>
<td>0.218</td>
<td>0.242</td>
<td>0.270</td>
<td>0.290</td>
</tr>
<tr>
<td>35</td>
<td>0.177</td>
<td>0.202</td>
<td>0.224</td>
<td>0.251</td>
<td>0.269</td>
</tr>
<tr>
<td>40</td>
<td>0.165</td>
<td>0.189</td>
<td>0.210</td>
<td>0.235</td>
<td>0.252</td>
</tr>
</tbody>
</table>

Over 40: 1.07/\(\sqrt{n}\), 1.23/\(\sqrt{n}\), 1.36/\(\sqrt{n}\), 1.52/\(\sqrt{n}\), 1.63/\(\sqrt{n}\)
3.6 Maintenance period analysis

On $\beta \sim 1$: Constant Failure Mode regarded as Exponential Distribution, we applied the technique of Failure Finding by calculating the inspection interval in the equation (10) [17]. Also, we created Excel Simulation to calculate the equation (10) in Figure 15, and the results on Assessment Guidelines for the maintenance of Reliability Engineering are summarized in Table 9.

$$A = 1 - \frac{FFI}{2M} \quad (10)$$

$A =$ Availability of the protective device (Ex. $A \geq 0.90$)

$FFI =$ The inspection interval ($t_i$)

$M =$ MTTF

Table 9: Sample of Assessment Guidelines in Maintenance and Reliability Engineering

<table>
<thead>
<tr>
<th>No.</th>
<th>Machine Code</th>
<th>Parameters</th>
<th>Type of Maintenance</th>
<th>Period of Maintenance (hours)</th>
<th>$A \geq 0.90$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Motor &amp; Pump 1</td>
<td>1.64093</td>
<td>PM</td>
<td>4,600</td>
<td>0.9037</td>
</tr>
<tr>
<td>2</td>
<td>Motor 2</td>
<td>22135.9</td>
<td>PM</td>
<td>4,400</td>
<td>0.9006</td>
</tr>
<tr>
<td>3</td>
<td>Motor 3</td>
<td>21433.1</td>
<td>PM</td>
<td>4,600</td>
<td>0.9037</td>
</tr>
</tbody>
</table>

In addition, we are able to develop the maintenance planning for the plant of Hard Chrome Plating in Figure 16 by applying reliability centered maintenance of the plant components inherent reliability value.
Figure 16: Sample of maintenance planning for the plant of Hard Chrome Plating.

3.7 Our model for cost engineering

The aim of the work is to develop a new equation representing the model to determine and optimize the maintenance costs which could be applied not only to the single component but to a set of components grouped in a particular way, i.e. to their criticality. At the same time, this new model allows to overcome some limits in the application of the classical one, when dealing with big dimensions plants. One of the problem is in fact due to the application of the classical model to a complex plant; the model forces to divided the plant by a very detailed tree-structure which is a very difficult task dealing with machines rich in components [18]. Another problem is represented by the meaning of the integral in the denominator of the equation; it represents an estimate of the service life of a component over a fixed time interval which must be the same for every component. Its meaning is in fact the substitution period provided by the analysis of the data sheets of the component i.e. without considering the real use in the plant or for example without considering repairs whereas possible [19]. So, the classical model does not take into account an historical study of all of the past conditions of the component to be analyzed, determining a loss of precision in the determination of the total maintenance costs and so providing a result in term of optimal maintenance interval which may be quite far from the true one [20].

As said, the proposed method tries to overcome these limits by a re-elaboration of the classical model; it introduces two important features represented by the possibility to apply the model to the whole machine and by the combination of the maintenance statistics of the firm and the probabilistic analysis about the components.

It is possible to manipulate the classical equation of maintenance costs to define a new model. As said, the classical equation (11) is as follows [21]:

\[
E(C_i) = \frac{E(C_{pi}) \cdot R_i(t_c) + E(C_{wi}) \cdot \left[1 - R_i(t_c)\right]}{\int_0^R R(x) \, dx}
\]  

(11)

The first step is to split this equation since it will be applied to a group of components rather than to a single one. Then, we need to define the equation (12) to (14).

\[
E_A(C_A) = \text{The equation of maintenance costs on Motor & Pump } 1
\]  

(12)

\[
E_B(C_B) = \text{The equation of maintenance costs on Motor } 2
\]  

(13)

\[
E_C(C_C) = \text{The equation of maintenance costs on Motor } 3
\]  

(14)

At the same way, Total \(E(C)\) must be redefined as the equation (15).

\[
\text{Total } E(C) = E_A(C_A) + E_B(C_B) + E_C(C_C)
\]  

(15)

So it is necessary to find some reliability function \(R(t)\) which represents the average of the \(R(t)\) functions of machinery on the equation (16) to (18).

\[
R_A(t_A) = h_A(t_A) = e^{\left(\frac{t_A}{t_a}\right)^a}
\]  

(16)

\[
R_B(t_B) = h_B(t_B) = e^{\left(\frac{t_B}{t_b}\right)^b}
\]  

(17)

\[
R_C(t_C) = h_C(t_C) = e^{\left(\frac{t_C}{t_c}\right)^c}
\]  

(18)

Moreover, by substituting and putting in evidence, we are able to state \(E_A(C_A), E_B(C_B), \) and \(E_C(C_C)\) on the equation (19) to (21).

\[
E_A(C_A) = \left[ E(C_{pa}) \cdot e^{\left(\frac{t_A}{t_a}\right)^a} \right]
\]  

(19)
Solving techniques on our mathematical problems

We tried to solve mathematical problems [22] of style in the equation (22).

\[ E(C_{\alpha}) = \left[ E(C_{\beta}) \left( e^{-\frac{x^2}{\alpha^2}} \right) \right] + E(C_{\omega}) \left[ 1 - \left( e^{-\frac{x^2}{\mu^2}} \right) \right] + \left[ \int_0^\infty \left( e^{-\frac{x^2}{\nu^2}} \right) dt \right] \]

\[ E(C_{\beta}) = \left[ E(C_{\beta}) \left( e^{-\frac{x^2}{\beta^2}} \right) \right] + E(C_{\omega}) \left[ 1 - \left( e^{-\frac{x^2}{\mu^2}} \right) \right] + \left[ \int_0^\infty \left( e^{-\frac{x^2}{\nu^2}} \right) dt \right] \]

Accordingly, we used Gauss Integration (Gaussian quadratures) for solving \[ \int \left( e^{-0.5 x^2} \right) dx \] in the following steps [23].

1. Converting coordinates from \( x \) to \( \xi \) before the integration by using Gauss Legendre formulas in Figure 17.

2. The Gaussian quadratures provide the flexibility of choosing not only the weighting coefficients (weight factors) but also the locations (abscissas) where the functions are evaluated. When the function is known and smooth, the Gaussian quadratures usually have decisive advantages in efficiency [24].

3. All Gaussian quadratures share the following equation (23).

\[ \int f(x) dx = \int \sum_{x=1}^n w(x) f(x) + R_n(x) \]

Where:

- \( x_n \), associated with zeros of orthogonal polynomials, are the integration points.
- \( w(x) \) is the weighting function related to the orthogonal polynomials.

4. Gauss-Legendre Formula: The Gauss-Legendre integration formula is the most commonly used form of Gaussian quadratures in the equation (24).

\[ \int_0^1 f(x) dx = \int_0^1 \left( e^{-0.5 x^2} \right) dx \]
Where:

\[ \xi_k \text{ is the } k^{th} \text{ zero of } P_n(\xi), \]
\[ w(\xi_k) = \frac{2}{(1-\xi_k^2)^2 P_n^2(\xi_k)}, \]
\[ g(\xi) = f\left(\frac{b-a}{2} \xi + \frac{b+a}{2}\right), \]
\[ R_n(\xi) = \frac{2^{2n+1} (n!)^4}{(2n+1)! [(2n)!]^3} g^{(2n)}(\xi). \]

Thus, we applied MATLAB and Excel about Gauss Integration for solving this model \( E(C) \) in Figure 18 and The total expected cost of planned maintenance per time: \( \text{Total } E(C) \) in Figure 19 [25].

5. Case Study Result

The model has been applied to the previous case study by the use of MATLAB and Excel software to generate simulation results. The analysis has been focused on the determination of the maintenance costs over a time period of 36 months after the data history analysis of the treated components of the plant, it is possible to show that Total \( E(C) \) consisted of 43% of \( E(C) \) on Motor & Pump 1, 32% of \( E(C) \) on Motor 2, and 25% of \( E(C) \) on Motor 3 in the trend of the reliability function for each criticality class. It can be said that, in spite of their main criticality, the element belonging to Motor & Pump 1 has higher maintenance costs; therefore, the element belonging to Motor 3 has low maintenance costs on analyzing costs which together contribute to generate the total maintenance costs from planned and unplanned maintenance costs.

5 Conclusions

We can make a comprehensive analysis of maintenance strategy and reliability requirements throughout the lifecycle of maintenance. The model has been applied to the previous case study by the use of integrated Reliability Theory on Hazard Rate for optimal cost of maintenance with the number of components in a semi automatic machine of coating to generate suitable results. The analysis has been focused on the determination of the cost throughout the lifecycle of maintenance.

The present work focused on the definition of a model to manage the costs necessary to extend the service life of a plant through the use of probabilistic
methods and Reliability Theory on Hazard Rate in order to better identify the importance of every components in a plant with respect to maintenance costs.

The new model is able to develop a methodology to determine maintenance costs which must be applied to some subsets of the elements of a plant, grouped according to their criticality.

The model allows also to overcome some limits of the classical model, providing a more precise determination of the costs. In fact, the previous data history of the components and the previous maintenance plans together with a probabilistic study are considered in the model to enhance the model to be more accurate [26].

Acknowledgements

We wish to express our thanks to the staff members of King Mongkut’s University of Technology North Bangkok and Italthai Group (Thailand), for their support during carrying out this research.

References

and Application, Taylor & Francis Group, 2013.


