Decision Mapping and Optimal Inspection Models for Plant Maintenance:  
Some Case Studies

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ABSTRACT

The need for an effective maintenance strategy and management system has been recognized as a very important and critical for reducing operational and maintenance costs, especially when the equipment increases in size and complexity. Selection of an appropriate and adequate maintenance and its frequency is considered to be crucial for failure free operation of plant equipment maintenance in process industries, particularly in desalination plants. In this paper a Decision Making Grid (DMG) technique has been applied to select the most suitable type of maintenance. Further, this paper outlines mathematical models that are applied to determine the optimum inspection frequency based on stochastic failures under preventive maintenance. Mean time between failures, mean time to repair and mean inspection time are fitted to compute optimum inspection frequency under preventive maintenance. Case studies from a desalination plant are presented based on the actual breakdown details and maintenance information. Keywords: Mean Time between Failures, Mean Time to Inspections, Mean Time to Repair, Condition Based Maintenance, Preventive Maintenance, Decision Making Grid.

1. INTRODUCTION

Modern production equipment has been designed with greater production capacity and higher reliability to meet the rigorous operating demands of industries, especially process industries. These improvements have also made the equipment more complex and challenging to maintain. Over the past few years, there is enormous emphasis to improve the maintenance performance. However if maintenance strategy is to be effective, it must be supported with a decision on adequate resources and maintenance information. Computerized maintenance system and decision models provide the maintenance planners to take decisions on how a plant should be maintained and how often and how much maintenance is to be done in an effective manner with minimum cost [1]. The application of various maintenance strategies during the life period could be established based on the failure pattern of any system. In Operate To Failure (OTF) or Breakdown Maintenance, machine is repaired once it fails and the downtime expected here is short. Fixed Time Maintenance (FTM) or Preventive Maintenance (PM) is a time-based strategy where maintenance actions are performed on a pre-determined, periodic basis. PM involves the repair, replacement, and maintenance of equipment in order to avoid unexpected failure [2]. The objective of any PM program is the minimization of the total cost of inspection and repair, and equipment downtime (measured in terms of lost production capacity or reduced product quality). The traditional approach in PM is based on the use of statistical and reliability analysis of equipment failure. Under statistical-reliability (S-R) based PM, the minimum total cost objective is pursued by establishing a “optimal” PM interval at which the equipment or system can be replaced or overhauled [3]. Condition Based Maintenance (CBM) approach involves the use of sensor-based monitoring of equipment condition in order to predict machine failure. Under condition-based maintenance, intervals between PM works are no longer fixed, but are performed only “when needed” [4]. Design Out Maintenance (DOM) and Skill Level upgrade (SLU) are also well considered maintenance strategies in industries. In DOM, the equipment is designed for minimum maintenance, but takes a long time to bring it back upon failure, whereas the machine can be repaired very fast upon failure in SLU.

2. DECISION MAKING GRID

Grid Analysis or Decision Making Grid (DMG) is a useful technique for making a decision on maintenance and considered to be powerful where a number of alternatives are available to choose from, and many different factors to take into account [5]. The DMG map has different levels/ranges as rows on a table, and the factors/criterion of maintenance as columns. The score of each option/factor combination is weighted and added these scores are accumulated to give an overall score for the option. DMG is an effective method that uses a multiple criteria for the evaluation of machine performance such as downtime and frequency of failures. DMG model is very effective in getting rid of critical problems of machines. Further, DMG deals with the selection of the appropriate maintenance strategy that is suitable for prioritizing failure analysis. When there are several options, DMG tool helps the maintenance engineer to choose the correct decision amongst other different factors [6].
3. MATHEMATICAL MODELS

3.1 Inspection models
The availability $A$ of an equipment or plant is given by a simple equation

$$A = \frac{R}{R + M}$$  \hspace{1cm} (1)

Where, $R$ is the Reliability and $M$ the Maintainability. MTBF (Mean Time Between Failures) is a measure of the reliability and is fixed for given equipment, whereas MTTR (Mean Time To Repairs) is a measure of maintainability[7]. The availability of machine can be increased by reducing the MTTR which could be possible only by an effective and meaningful maintenance strategy. The maintenance decision is primarily related to inspection of machine for finding the working condition. The inspection of machine can be optimized based on past information on the machine and their interpretations. Decision on optimal inspection could be complicated as it entails consideration of cost, down time, production demand, preventive maintenance shut down and survival time etc. Further, for a constant failure rate ($\lambda$) of a machine, the following simple relation for the examination interval can be deduced [4]:

$$e^{\lambda-i} - \lambda i = 1 + \lambda C_p$$  \hspace{1cm} (2)

where $c_i$ is the examination cost and $c_p$ is the unitary downtime cost or cost of repair.

Our goal is to determine the inspection policy which minimizes the total downtime per unit time incurred due to a breakdown as well as to maximize the profit per unit time. The total down time $D(n)$ is considered as sum of down time incurred due to repairs per unit time and inspection per unit time[8]. This will give rise to equation 3.

$$D(n) = \frac{\lambda n}{\mu} + \frac{n}{i}$$  \hspace{1cm} (3)

Where $\mu$ is the Mean Service rate and $i$ is the Mean inspection rate = $1$/MTTI (Mean Time To Inspection). Differentiating above equation,

$$\frac{d}{n}[D(n)] = \frac{\lambda n}{\mu} + \frac{1}{i} \text{ and hence } \lambda i = \frac{\mu}{i}$$  \hspace{1cm} (4)

Substituting for $\lambda(n) = \frac{K}{n}$ and $\lambda'(n) = \frac{K}{n^2}$; where the K can be interrupted as the arrival rate of break-downs per unit time when one inspection is made per unit time. We obtain an expression for inspection frequency to minimize the down time as

$$n(D) = \frac{\mu}{K}$$  \hspace{1cm} (5)

We can extend equation 5 for maximization of profit as

$$n(P) = \frac{\mu}{K} \left[ \frac{C_u + \frac{\mu}{K} C_p}{C_u + \frac{\mu}{K} c_i} \right]$$  \hspace{1cm} (6)

Where $C_u$ is the profit of the value of the output in an uninterrupted unit of time if there is no downtime losses, $C_i$ is the average cost of inspection.

3.2 Preventive Maintenance replacement models
There are two basic preventive maintenance policies for the systems that are subject to stochastic failure. They are age-based replacement policy and constant-interval replacement policy [9].

According to age-based replacement policy, preventive replacement is performed after $t_p$ hours of continuous operation without failure. If the system fails prior to $t_p$, maintenance (replacement) is performed at the time of failure and preventive maintenance is rescheduled after the same $t_p$, operational hours.

In a constant-interval replacement policy, preventive replacement is performed after it has been operating for the total $t_p$ hours, regardless of the number of intervening failures. If a failure occurs prior to $t_p$, only a minimal repair is performed. Minimal repair does not change the failure rate of the system and preventive maintenance (replacement) renews the system and it becomes as good as new.

An age-based replacement policy is generally suited for simple equipment or single-units in which repair at the time of failure (replacement) corresponds to a general overhaul. A constant-interval replacement policy is suited for complex systems like engines and turbines which has a larger number of units within itself. In this paper, the constant-interval replacement policy is reviewed to determine the optimal time for preventive maintenance, $t_p$, as age-based replacement policy is relevant to simple equipment only [10].

Total expected cost of preventive and breakdown maintenance per unit time,

$$UC(t_p) = \frac{\text{Total expected cost due to PM & minimal repairs}}{\text{Expected length of interval}}$$

$$= \frac{C_u + sH(t_p)}{t_p}$$  \hspace{1cm} (7)

Where, $H(t_p) = \int_0^{t_p} \lambda(t) d\tau \quad \lambda(t)=k R(t)$ and $C_u$ is the unitary downtime cost or cost of repair and $C_p$ is the cost of PM replacement.

And $f(t)$ is Time-to-failure probability density function, $R(t)$ is the reliability and $t_p$ is Time for preventive replacement. The optimal $t_p$ is the value of $t_p$that minimize the function $UC(t_p)$.

4. CASE STUDIES:

4.1 Decision Making Grid
In this paper, the selection of appropriate maintenance strategy for a desalination plant is devised using DMG. The approach adopted here is categorizing the desalination plant failures by considering their downtimes and frequency of failures. Various factors are taken into account while developing DMG model such as machine criticality, downtime, frequency of failures, machine age and other operational limitations.

The following steps are used to implement the DMG for the desalination plant.

Step 1: Criteria Analysis: In this step, an attempt is made to assess how badly the component is performed for a period of two years’ time. The worst performers are sorted and placed into high, medium, and low sub groups according to number of failures and down time as shown in Table 1. It is a priority table.
Step 2: Decision Mapping: The aim of this step is to monitor the worst component of the desalination unit on a grid as shown in Figure 1. This is done by assigning the type of maintenance to be followed depends upon the down time. Here the grid acts as a map on which the performance of worst components is located according to multiple criterions.

Table 1: Data Analysis for the DMG

<table>
<thead>
<tr>
<th>Name</th>
<th>Down Time (hours)</th>
<th>Name</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube Leaks</td>
<td>48</td>
<td>Tubes Leaks</td>
<td>15</td>
</tr>
<tr>
<td>Bundle Fouling and Scaling</td>
<td>48</td>
<td>Bundle Fouling and Scaling</td>
<td>25</td>
</tr>
<tr>
<td>Screen Jetting</td>
<td>48</td>
<td>Screen Jetting</td>
<td>6</td>
</tr>
<tr>
<td>Filters (Demister)</td>
<td>48</td>
<td>Gaskets</td>
<td>5</td>
</tr>
<tr>
<td>Chemical Air Pumps</td>
<td>24</td>
<td>Feed Pump</td>
<td>5</td>
</tr>
<tr>
<td>Feed pumps failure</td>
<td>24</td>
<td>Chemical Air Pumps</td>
<td>5</td>
</tr>
<tr>
<td>Gaskets</td>
<td>12</td>
<td>Pin Hole Leaking</td>
<td>5</td>
</tr>
<tr>
<td>Pin Hole Leaking</td>
<td>12</td>
<td>Vales Failure</td>
<td>4</td>
</tr>
<tr>
<td>Valve Failure</td>
<td>12</td>
<td>Loss of Vacuum</td>
<td>2</td>
</tr>
<tr>
<td>Temperature Gauges</td>
<td>12</td>
<td>Temperature Gauges</td>
<td>2</td>
</tr>
<tr>
<td>Chemical Drum Leaking</td>
<td>12</td>
<td>Bolts broken</td>
<td>2</td>
</tr>
<tr>
<td>Loss of Vacuum</td>
<td>6</td>
<td>Chemical drum Leaking</td>
<td>1</td>
</tr>
<tr>
<td>Instrument line failure</td>
<td>6</td>
<td>Instrument line failure</td>
<td>1</td>
</tr>
<tr>
<td>Sample point clogging</td>
<td>6</td>
<td>Sample point clogging</td>
<td>1</td>
</tr>
<tr>
<td>Bolts broken</td>
<td>6</td>
<td>Filters (Demister)</td>
<td>1</td>
</tr>
<tr>
<td>Broken knobs of pumps</td>
<td>6</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Loosen of different types of flanges</td>
<td>3.6</td>
<td>Loosen of different types of flanges</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 1: Decision Mapping
Step 3: Multi leveled decision support: Once the worst performing machines are identified and the appropriate action is suggested, it is now moved from strategic systems level to the operational component level [11]. Figure 2 represents criteria of evaluation (objectives), types of machine, failure categories and failure details etc. The criteria evaluation is based on downtime (in minutes or months), frequency of failure, spare parts requirement and bottlenecks in work execution. Further, these criteria are mapped under various failure categories and then fault details are assimilated. Interrelationship between the criteria and failure modes are indicated by arrows. Table 2 depicts the DMG obtained from a multilevel decision support based on Figure 2.

![Decision Making Grid](image)

**Table 2**

<table>
<thead>
<tr>
<th>Sl No</th>
<th>Downtime</th>
<th>Frequency</th>
<th>Failure Name</th>
<th>Decision taken</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low</td>
<td>Low</td>
<td>Instrument air, sample point, flanges, Pumps broken knobs</td>
<td>OTF</td>
</tr>
<tr>
<td>2</td>
<td>Low</td>
<td>Medium</td>
<td>Bolts</td>
<td>FTM</td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>High</td>
<td>Nil</td>
<td>SLU</td>
</tr>
<tr>
<td>4</td>
<td>Medium</td>
<td>Low</td>
<td>Chemical Drum</td>
<td>FTM</td>
</tr>
<tr>
<td>5</td>
<td>Medium</td>
<td>Medium</td>
<td>Pin Hole, Valves, Temperature Gauges, Desal Inside Vacuum</td>
<td>FTM</td>
</tr>
<tr>
<td>6</td>
<td>Medium</td>
<td>High</td>
<td>Gaskets</td>
<td>FTM</td>
</tr>
<tr>
<td>7</td>
<td>High</td>
<td>Low</td>
<td>Filter (Demister)</td>
<td>CBM</td>
</tr>
<tr>
<td>8</td>
<td>High</td>
<td>Medium</td>
<td>Nil</td>
<td>FTM</td>
</tr>
<tr>
<td>9</td>
<td>High</td>
<td>High</td>
<td>Tubes Leaks, Bundle Fouling, Chemical Air Pump, Feed Pump, Screen Jetting</td>
<td>DOM</td>
</tr>
</tbody>
</table>

The DMG model developed and proposed for implementation could support the decision making on strategies of maintenance for equipment in the desalination plant.

4.2 Inspection models

Maintenance records were reviewed and the breakdown and maintenance information are obtained for determining optimum inspection frequency. The optimum inspection frequency based on cost and downtime computed using the model described by equation 5 and 6 is exhibited in Table 3. Here, the inspection cost per month and cost of products per month (production loss) are taken as RO (Rial Omani) 2,750 and 20,910 respectively.
Table 3

Optimum Inspection Frequency

<table>
<thead>
<tr>
<th>SL.NO</th>
<th>Inspection items</th>
<th>K</th>
<th>MTTR (Minutes)</th>
<th>MTTI (Minutes)</th>
<th>Cost of Repair in RO</th>
<th>Optimal Inspection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tube Leaks</td>
<td>0.625</td>
<td>192</td>
<td>30</td>
<td>3251</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Bundle Fouling and Scaling</td>
<td>1</td>
<td>120</td>
<td>60</td>
<td>114</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>Screen Jetting</td>
<td>0.25</td>
<td>480</td>
<td>15</td>
<td>179</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Filters</td>
<td>0.042</td>
<td>288</td>
<td>30</td>
<td>9.6</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Chemical Air pumps</td>
<td>0.21</td>
<td>288</td>
<td>30</td>
<td>52</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>Feed Pumps Failure</td>
<td>0.21</td>
<td>288</td>
<td>60</td>
<td>62</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>Gaskets</td>
<td>0.21</td>
<td>144</td>
<td>30</td>
<td>27</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>Pin Hole Leaking</td>
<td>0.125</td>
<td>240</td>
<td>30</td>
<td>19</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>Valves failures</td>
<td>0.21</td>
<td>144</td>
<td>60</td>
<td>51</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>Chemical drum Leaking</td>
<td>0.042</td>
<td>720</td>
<td>15</td>
<td>29</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>Bolts broken</td>
<td>0.083</td>
<td>180</td>
<td>30</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>Instrument failure</td>
<td>0.042</td>
<td>360</td>
<td>30</td>
<td>22</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>Sample point clogging</td>
<td>0.042</td>
<td>360</td>
<td>40</td>
<td>7.5</td>
<td>1</td>
</tr>
<tr>
<td>14</td>
<td>Loss of vacuum while starting</td>
<td>0.083</td>
<td>180</td>
<td>60</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>Pumps Control</td>
<td>0.042</td>
<td>360</td>
<td>15</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>Temperature Gauges</td>
<td>0.125</td>
<td>120</td>
<td>15</td>
<td>27</td>
<td>1</td>
</tr>
<tr>
<td>17</td>
<td>Flanges</td>
<td>0.042</td>
<td>216</td>
<td>20</td>
<td>6</td>
<td>1</td>
</tr>
</tbody>
</table>

4.3 Replacement models

The breakdown details of the three similar sea water pumps for past three years (36 month) were studied. It is assumed that during three years this equipment follows a uniform time to failure probability density function. Considering pump 1, the cost of preventive replacement is RO 337 and the cost of failure replacement is RO 1500, the optimal time for preventive replacement can be estimated as follows,

\[
f(t) = \frac{1}{3} e^{-t/3}, \quad 0 \leq t \leq 36
\]

\[
R(t) = 1 - f(t)
\]

\[
\lambda(t) = \frac{f(t)}{R(t)} = \frac{1}{3} e^{-t/3} = \frac{1}{3} e^{-t/3}
\]

\[
H(t_p) = \int_0^{t_p} \lambda(t)d t = \int_0^{t_p} \frac{1}{3} e^{-t/3} dt = \frac{1}{3} e^{-t_p/3}
\]

\[
UEC(t_p) = \frac{C_F}{C_P} H(t_p) = \frac{1500}{337} \frac{1}{3} e^{-t_p/3}
\]

The expected cost of PM is computed for different values of time as depicted in Table 4. The value of \(t_p\) that gives the lowest expected cost (UEC) is shown in Figure 3.

Table 4

Expected cost of PM

<table>
<thead>
<tr>
<th>Cost of failure replacement (RO)</th>
<th>Cost of Preventive Maintenance (RO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25</td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td>337</td>
</tr>
<tr>
<td>1700</td>
<td>460</td>
</tr>
<tr>
<td>1100</td>
<td>515</td>
</tr>
</tbody>
</table>
5. CONCLUSION

Sea water desalination is extremely vital for the daily life activities and for the development of GCC states like Sultanate of Oman. The desalination plant has been suffering from frequent shutdowns and repairs over the past years. It is apparent that there is a lack of a proper maintenance strategy which could reduce down time and unwarranted failures. Based on the analysis that was carried out, a DMG model has been developed for the selection of appropriate maintenance strategies in order to reduce the frequency of failures and the downtime of the desalination plant. The DMG model developed is very effective in getting rid of critical problems of machines and to select appropriate maintenance strategy for the Desalination plant considering various aspects such as downtime, frequency of failure, spare parts, failure modes etc. A fair estimate of inspection frequency has been derived considering MTTR, MTTI, breakdown details and various cost elements. Implementing the inspection models obtained can reduce the frequency of failures and will prolong useful operating time of plant equipment. Further, the mathematical model has been applied to determine optimum replacement for seawater pumps under constant interval replacement policy. The result shows that the optimum PM replacement is influenced by failure rate, cost of replacement and cost of PM instead of a fixed schedule.

REFERENCES