Performance Analysis of Port Cranes

S M Rizwan¹ and Mathew AG²
¹Department of Mathematics and Statistics, Caledonian College of Engineering, Sultanate of Oman
²Department of Mechanical Engineering, College of Applied Sciences, Sultanate of Oman
rizwan@caledonian.edu.om

Abstract

The paper presents a performance analysis of the cranes operating at the port. Cranes at the port are generally used for loading and unloading of heavy or stroppy loads/vessels on and off ships. Performance of any system could be gauged in terms of its reliability and availability. Four years maintenance data of a particular crane has been collected. The values of different failure / repair / replacement rates are estimated from the data to be used in this analysis. The crane fails due to the failures which are repairable (minor electrical or mechanical failure) and the failures where only replacement is possible (major electrical or mechanical failure). An inspection is carried out to identify the type of the electrical or mechanical failure. The performance analysis of the crane has been carried out and as a result, measures of cranes effectiveness such as mean time to crane failure and crane availability are estimated numerically by using semi-Markov processes and regenerative point techniques.

Keywords—Port Cranes, failures, repairs, Semi – Markov, regenerative processes

NOTATIONS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>Operative state of the crane</td>
</tr>
<tr>
<td>□</td>
<td>Failed state of the crane</td>
</tr>
<tr>
<td>α</td>
<td>Inspection rate</td>
</tr>
<tr>
<td>FREPAIR</td>
<td>Minor failure is under inspection</td>
</tr>
<tr>
<td>FREPLACEMENT</td>
<td>Major failure is under inspection</td>
</tr>
<tr>
<td>FE</td>
<td>Electrical failed unit is under repair/replacement</td>
</tr>
<tr>
<td>FM</td>
<td>Mechanical failed unit is under repair/replacement</td>
</tr>
<tr>
<td>λ₁</td>
<td>Failure rate of the cranes due to minor reasons (repairable)</td>
</tr>
<tr>
<td>λ₂</td>
<td>Failure rate of the cranes due to major reasons (replaceable)</td>
</tr>
<tr>
<td>p₁</td>
<td>Probability of electrical failure (repairable)</td>
</tr>
<tr>
<td>p₂</td>
<td>Probability of mechanical failure (repairable)</td>
</tr>
<tr>
<td>p₁'</td>
<td>Probability of electrical failure (replaceable)</td>
</tr>
<tr>
<td>p₂'</td>
<td>Probability of mechanical failure (replaceable)</td>
</tr>
</tbody>
</table>
Probability density function (p.d.f.), cumulative distribution function (c.d.f.) of the first passage time from a regenerative state \(i\) to \(j\) or to a failed state \(j\) in \((0, t]\).

\(i(t), I(t)\) pdf, c.d.f. of inspection time of a failed unit

\(g_1(t), G_1(t)\) p.d.f., c.d.f. of repair time of electrically failed unit

\(g_2(t), G_2(t)\) p.d.f., c.d.f. of repair time of mechanically failed unit

\(g_3(t), G_3(t)\) p.d.f., c.d.f. of replacement time of electrically failed unit

\(g_4(t), G_4(t)\) p.d.f., c.d.f. of replacement time of mechanically failed unit

\(\phi_i(t)\) c.d.f. of first passage time from a regenerative state \(i\) to a failed state \(j\)

\[\int_0^t f(t-u)g(u)du\]

1. Introduction

Complex systems are commonly used in industries and therefore researchers have spent a great deal of efforts in analyzing such systems as to how such complex system performs. Performance of any system could be gauged through achieved reliability indices which in turn are the indicative of the overall system behavior. Rizwan et. al [2] analyzed a waste water treatment plant and obtained various reliability indices to gauge the system performance. Mathew et. al [3] analyzed a Continuous casting plant and obtained the reliability indices. Rizwan et. al [4] and Padmavathi et. al [5] have contributed in this area where the performance analysis of a desalination plant was carried out. A book by Kuo & Zuo [1] could be referred for the detailed study of the literature cited. In all these researches, the outcome was mainly focusing on the system performances of the industrial systems using mathematical modeling. The real maintenance situations noted in the data are generally embedded in the model for system analysis.

A potential application of the reliability concepts could also be explored for performance analysis of cranes at the port. The indicators of the analysis could be useful in optimizing the existing maintenance policies with a scope of further improvements. Cranes at the port are generally used for loading and unloading of heavy or stroppy loads/vessels on and off ships. Generally, the cranes operate round the clock and are occupied most of the time. Due to the heavy traffic and limited harboring facility at the port, it is quite essential that the cranes keep functioning and keep clearing the transporting ships within the specified time limit. In order to attain the maximum cranes reliability, their performances need to be monitored and proper preventive maintenance plans need to be in place. For the purpose of this analysis, four years maintenance data of a particular crane has been collected and the real estimated values of various rates (failure/repair/replacement rates) are used for obtaining reliability results. Any major failure brings the crane to a complete halt and stops functioning until restored. Data reveals that the crane fails due to the failures which are repairable (minor electrical or mechanical failure) and the failures where only replacement is possible (major electrical or mechanical failure). An inspection is carried out to identify the type of the electrical or
mechanical failure. The performance analysis of the cranes have been carried out and as a result, measures of cranes effectiveness such as mean time to crane failure and cranes availability are estimated numerically. Semi-Markov processes and regenerative point techniques are used in the entire analysis.

Using the data, following values of failure/repair/replacement rates are estimated for this crane:

- Estimated value of repairable failure rate $\lambda_1 = 0.000070163/\text{hr}$.
- Estimated value of replaceable failure rate $\lambda_2 = 0.000053457/\text{hr}$.
- Estimated value of electrical repair rate $(\alpha_1) = 0.0833/\text{hr}$.
- Estimated value of mechanical repair rate $(\alpha_2) = 0.0833/\text{hr}$.
- Estimated value of electrical replacement rate $(\alpha_3) = 0.0833/\text{hr}$.
- Estimated value of mechanical replacement rate $(\alpha_4) = 0.0833/\text{hr}$.
- Probability that the unit needs electrical repair ($p_1$) = 0.135
- Probability that the unit needs mechanical repair ($p_2$) = 0.594
- Probability that the unit needs electrical replacement ($p_3$) = 0.027
- Probability that the unit needs mechanical replacement ($p_4$) = 0.243

2. Model Description and Assumptions

- The unit is initially operative at state 0 and transits probabilistically depending on the type of failure / repair to any of the 6 states 1 to 6 with different rates / probabilities as shown in Fig.1.
- All failure times are exponentially distributed whereas other times have general distributions.
- After each repair / replacement, the unit works as good as new.
- Breakdowns are self-announcing but the type of failure is identified through inspection.
- The unit is brought into operation as soon as possible.

3. Transition Probabilities and Mean Sojourn Times

A state transition diagram showing the possible states of transition of the plant is shown in Fig. 1. The epochs of entry into states 0, 1, 2, 3, 4, 5 and 6 are the regenerative points and hence these states are regenerative states. The transition probabilities are given by:

$$dQ_{01} = \lambda_1 e^{-\lambda_1 t} dt$$
$$dQ_{02} = \lambda_2 e^{-\lambda_2 t} dt$$
$$dQ_{13} = p_1 \alpha e^{-\alpha t} dt$$
$$dQ_{14} = p_2 \alpha e^{-\alpha t} dt$$
$$dQ_{25} = p_1 \alpha e^{-\alpha t} dt$$
The non-zero elements $p_{ij}$ are given below:

- $p_{01} = p_{02} = 1$
- $p_{13} = p_{14} = p_2$, $p_{25} = p_1$, $p_{26} = p_2'$
- $p_{30} = p_{40} = p_{50} = p_{60} = 1$

By these transition probabilities, it is also verified that:

- $p_{01} = p_{02} = 1$
- $p_{13} + p_{14} = p_1 + p_2 = 1$
- $p_{25} + p_{26} = p_1' + p_2' = 1$
- $p_{30} = p_{40} = p_{50} = p_{60} = 1$

The unconditional mean time taken by the system to transit for any regenerative state ‘$j$’ when it (time) is counted from the epoch of entrance into state ‘$i$’ is mathematically stated as:

\[ \mu_j = \frac{1}{\alpha_i} \] (11 - 16)
Thus,

\[ m_{ij} = \int_0^x t dQ(t) = -q_i g'(0) \]

Therefore,

\[ m_{01} = m_{02} = \mu_0 \]
\[ m_{13} + m_{14} = \mu_1 \]
\[ m_{25} + m_{26} = \mu_2 \]
\[ m_{30} = \mu_3 \]
\[ m_{40} = \mu_4 \]
\[ m_{50} = \mu_5 \]
\[ m_{60} = \mu_6 \]

\[ (17-23) \]

4. The Mathematical Analysis

4.1 Mean Time to Crane Failure

Regarding the failed states as absorbing states and employing the arguments used for regenerative processes, the following recursive relation for \( \phi_i(t) \) is obtained:
\[ \phi_0(t) = Q_{01}(t) + Q_{02}(t) \]  

Solving the above equation for \( \phi_0^*(s) \) by taking Laplace Stieltje’s Transforms and using the determinant method, the following is obtained:

\[ \phi_0^*(s) = \frac{N(s)}{D(s)} \]  

(27)

Where, \( N(s) = Q_{01}^{**}(s) + Q_{02}^{**}(s) \) and \( D(s) = 1 \)

Now the mean time to crane failure (MTCF) when the unit started at the beginning of state 0, is:

\[ \text{MTSF} = \lim_{s \to 0} \frac{1 - \phi_0^*(s)}{s} = \frac{N}{D} \]  

(28)

Where, \( N = \mu_0 \) and \( D = 1 \)

### 4.2 Availability Analysis of Unit of the Plant

Using the probabilistic arguments and defining \( A_i(t) \) as the probability of the unit entering the upstate at instant \( t \), given that the unit entered in regenerative state \( i \) at \( t=0 \), the following recursive relations are obtained:

\[
\begin{align*}
A_0(t) &= M_0(t) + q_{01}(t) \odot A_1(t) + q_{02}(t) \odot A_2(t) \\
A_1(t) &= q_{13}(t) \odot A_3(t) + q_{14}(t) \odot A_4(t) \\
A_2(t) &= q_{25}(t) \odot A_5(t) + q_{26}(t) \odot A_6(t) \\
A_3(t) &= q_{30}(t) \odot A_0(t) \\
A_4(t) &= q_{40}(t) \odot A_0(t) \\
A_5(t) &= q_{50}(t) \odot A_0(t) \\
A_6(t) &= q_{60}(t) \odot A_0(t)
\end{align*}
\]  

(29–35)

Where, \( M_0(t) = e^{-(\lambda_1 + \lambda_2)t} \)

Taking Laplace Transforms of the above equations and solving them for \( A_0^*(s) \), the following is obtained:

\[ A_0^*(s) = \frac{N_1(s)}{D_1(s)} \]  

(36)

Therefore, the steady-state availability of the crane is given by:
\[ A_0 = \lim_{s \to 0} sA_0(s) = \frac{N_1}{D_1} \]  

(37)

Where, 

\[ N_1 = \mu_0, \]  
\[ D_1 = \mu_0p_1 + \mu_1p_1 + \mu_3p_1 + \mu_4p_2 + \mu_1p_2 + \mu_6p_2 + \mu_2p_1 + \mu_0p_1 + \mu_2p_1 + \mu_0p_2 + \mu_0p_2 + \mu_6p_2 \]

5. Particular Case

For the particular case, the following are considered:

\[ g_1(t) = \alpha_1 e^{-\alpha_1 t}, \]  
\[ g_2(t) = \alpha_2 e^{-\alpha_2 t}, \]  
\[ g_3(t) = \alpha_3 e^{-\alpha_3 t}, \]  
\[ g_4(t) = \alpha_4 e^{-\alpha_4 t} \]

\[ p_{01} = p_{02} = 1, \]  
\[ p_{13} = p_{14} = p_{12}, \]  
\[ p_{25} = p_{13}, p_{26} = p_{22}^{'}, \]  
\[ p_{30} = p_{40} = p_{50} = p_{60} = 1 \]

\[ \mu_0 = \frac{1}{\lambda}, \mu_1 = \frac{1}{\alpha}, \mu_2 = \frac{1}{\alpha_1}, \mu_3 = \frac{1}{\alpha_2}, \mu_4 = \frac{1}{\alpha_2}, \mu_5 = \frac{1}{\alpha_3}, \mu_6 = \frac{1}{\alpha_4} \]

Using the data as summarized in section 1 and the reliability expressions obtained in section 4, the following values reflects the crane performance:

Mean time to crane failure = 8089 hours

Availability of the crane \((A_0) = 0.999351485\)

6. Conclusions

The model incorporates the actual breakdowns situations and offers a scientific basis for performance analysis of the cranes. It has been noted that the expected time for which the crane is in operation before it completely fails is about 8089 hours, which is one of the measure of its reliability. Also, the probability that the crane will be able to operate within the tolerances for a specified period of time is 0.999558.

References

[4] S M Rizwan, Padmavathi N, Anita Pal & Gulshan Taneja, “Reliability Analysis of a seven unit desalination plant with shutdown during winter season and repair/maintenance on FCFS
