4. Modeling maintenance and repair costs using stochastic point processes for life cycle costing of repairable systems

4.1 Introduction

The objective of this chapter is to present a methodology based on the reliability and maintainability principles for effective implementation of life cycle costing in design and procurement of repairable systems. In the previous chapter, the important life cycle stages for repairable systems are identified and a general model is proposed. In this chapter, mathematical equations have been formulated for the life cycle stages such as acquisition, installation and commissioning, operation, maintenance and repair and disposal. The focus is mainly on modelling the maintenance and repair cost which is one of the major elements of repairable system life cycle cost. To model maintenance and repair costs, the stochastic point process approach is employed. The life time of repairable system is modelled using a two parameter Weibull distribution. The expected number of failures are estimated based on the assumption that the number of replacements of the components in an interval \((0, t)\) follow renewal process in first case and minimal repair process in second case. Based on the expected number of failures, the life time maintenance and repair costs are estimated for as-good-as-new and as-bad-as-old after repair states of repairable systems. A methodology to decide whether a renewal approach or minimal repair approach should be planned for a particular component is also presented. The developed generalized model is illustrated through a specific application, namely an industrial pump and the results obtained are presented. The proposed model is believed to be a simple way for system designers to estimate and compare the life cycle cost of their different design alternatives at system design stage using system reliability and maintainability parameters.

This chapter starts with an introduction to sustainment dominated products followed by the discussion on various after-repair-states of repairable systems. Four main stochastic point process models applied to repairable systems are briefly discussed. The equations to estimate expected number of failures for renewal process and minimal repair process are then presented. The formulation of equations to estimate individual cost components of the model are presented in section 4.5. Section 4.6 presents a detailed case study on a typical pump from industry. Finally, conclusions are drawn based on the analysis carried out and the results obtained.
4.2 Sustainment dominated products

In the normal course of product development, it often becomes necessary to change the design of products and systems consistent with shifts in demand and with changes in the availability of the materials and components from which they are manufactured (Sandborn and Myers, 2008). When the content of the system is technological in nature, the short product life cycle associated with fast moving technology changes becomes both a problem and an opportunity for manufacturers and systems integrators. For most high-volume, consumer oriented products and systems, the rapid rate of technology change translates into a critical need to stay on the leading edge of technology. These product sectors must adapt the newest materials, components, and processes in order to prevent loss of their market share to competitors. For leading-edge products, updating the design of a product or system is a question of balancing the risks of investing resources in new, potentially immature technologies against potential functional or performance gains that could differentiate them from their competitors in the market. Examples of leading-edge products that race to adapt to the newest technology are high-volume consumer electronics, e.g., mobile phones and PDAs. For such products, the cost of sustaining is not that significant and the life cycle cost is normally dominated by their initial acquisition cost.

There are however, significant product sectors that find it difficult to adopt leading-edge technology. Examples include airplanes, ships, computer networks for air traffic control and power grid management, industrial equipment and medical equipment. These product sectors often “lag” the technology wave because of the high costs and/or long times associated with technology insertion and design refresh. Many of these product sectors involve “safety critical” systems where lengthy and expensive qualification/certification cycles may be required even for minor design changes and where systems are fielded (and must be maintained) for long periods of time (often 20 years or more). Because of these attributes, many of these product sectors also share the common attribute of being sustainment dominated, i.e., their long-term sustainment (life cycle) costs exceed the original procurement costs for the system. For such products, the life time sustainment cost often dominates the life cycle cost. Therefore, especially for such systems the life cycle cost analysis becomes quite essential. A case study of an industrial pump presented in this chapter is also an example of a sustainment dominated product where the long-term sustainment costs are very much higher than its initial procurement cost.
4.3 After-repair-states

In the real world, it is very obvious that most systems, such as automobiles, aircrafts and computers are designed to be repaired rather than replaced upon failure. A system is described to be repairable when after it has failed to perform at least one of its intended functions can be restored to fully satisfactory performance by any method other than replacement of the entire system. The restoration can be done by any action including changing of parts, changes to adjustable settings, swapping of components or even a sharp blow with a hammer. For example a laptop computer not connected to electrical power may fail to start when the battery is dead. In this case, replacing the battery with a new one solves the problem. A television set is obviously another example of a repairable system which upon failure may be restored possibly to satisfactory performance by simply replacing either the failed resistor or transformer if that is the cause, or by adjustments to the sweep or synchronization settings. Thus, in case of repairable systems, with the ability to repair or restore a failed system, a failure-repair-failure-repair cycle is generated (Eb ling 2002). For such systems, the components can be repaired or adjusted rather than replaced, whenever a breakdown occurs.

As a result of the repair actions, a repairable system may end up in one of the four possible states after repairs. These include as-good-as-new, as-bad-as-old, better-than-old-but-worse-than-new and worse-than-old. For a repairable system to be in ‘as-good-as-new’ state after repairs an item upon failure is replaced and it is assumed that the system is restored to its original condition. Such a process is also called as a renewal process wherein the mean times between failures are independent and identically distributed. When the repair or substitution of the failed part in a system does not involve a significant modification of the reliability of a system and the failure rate after repairs is same as the failure rate just prior to failure, then the system ends in ‘as-bad-as-old’ state. This process is also called as minimal repair process which leaves the system in approximately the same state it was in just prior to failure. Under the condition of imperfect repair, where the reliability after repair is better than just before failure, the system ends in ‘better-than-old-but-worse-than-new’ state. The imperfect repair is defined as the repair that is perfect with probability p and minimal with probability 1- p. In case of hazardous maintenance and repair the system ends in ‘worse-than-old’ state wherein the condition of system is worse after repair than it was before failure. In this thesis, the as-good-as-new and as-bad-as-old after-repair states are evaluated from LCC perspective.
4.4 Stochastic point processes

In case of repairable system the reliability is best modelled using stochastic point processes. The number of failures in an interval of time can be represented through a stochastic point process. The stochastic point process is characterized by isolated events (failures) occurring at instants distributed randomly over a time continuum. The point process can be interpreted as a counting process that counts the number of failures in a certain time interval. Such a process is called as time truncated when it stops counting at a particular instant and is often referred as failure truncated when it stops counting when a certain number of failures are reached. Figure 4.1 shows various stochastic point processes used in case of repairable systems.

**Figure 4.1 Stochastic point processes for repairable systems**

Four main stochastic process models as applied to model the repairable systems are discussed below:

1. **Repair to original condition (as-good-as-new)**
   - Renewal Process (RP)
   - Homogeneous Poisson Process (HPP)

2. **Minimal Repair (as-bad-as-old)**
   - Superimposed Renewal Process (SRP)
   - Non-homogeneous Poisson Process (NHPP)

The renewal process is used to represent time-to-failure data that are independent and identically distributed. The system after repairs is restored to its original condition, or “as-good-as-new”. The HPP is a special case of RP where the times between failures are exponentially distributed identical and independent. The time to failure is described by exponential distribution with constant failure rate. The superimposed renewal process is derived from the combination of various independent renewal processes. NHPP is able to correctly describe the failure-repair process when the repair or substitution of the failed
part in a given system does not involve a significant modification of the system reliability. This will leave the system in approximately the same state it was just prior to failure and the failure rate of the item after repairs will be same as the failure rate just prior to failure.

4.4.1 Expected number of failures for renewal process

As stated earlier, in case of repairable systems a component can be repaired or adjusted rather than replaced when a breakdown occurs. The expected time to failure after repair is different from the expected time to first failure of a new component. The renewal process approach does not take this into account and the time to first failure is assumed to be valid for every subsequent failure of the component. Thus, the time between failures are assumed to be independent and identically distributed. It is assumed that after each failure the system is repaired to a condition as-good-as-new (repair to original condition). If \( N(t) \) is the total number of failures by time \( t \) and MTBF is the mean time between failures, then the expected number of failures for renewal process in the interval \((0, t)\) are estimated as follows:

\[
E[N(t)] = \frac{t}{MTBF}
\]  

(4.1)

4.4.2 Expected number of failures for minimal repair process

Whenever trend is present in time between failures data, the regular distribution fitting methods are not valid and one has to rely on a non-stationery model such as NHPP. Under such circumstances, the minimal repair process approach can be employed. The NHPP allows modeling of trend in the number of failures to be found in an interval in relation to total age of the system through the intensity function. Under the condition of minimal repair, the repair or substitution of a failed part does not involve a significant modification of system reliability. Minimal repair is defined as the situation when the system reliability characteristics are not visibly changed by the repair action. The system failure rate is same as the failure rate just before failure. As a result of minimal repair, the times between failures may no longer be independent and identically distributed. The system is repaired only to the state it was immediately before failure. A minimal repair usually corresponds to repairing or replacing only a minor part of the system. The system will continue to deteriorate over time. A useful way to model this situation is to treat it as a stochastic point process. To model this point process, an intensity function, \( \rho(t) \), can be defined as a rate of change of the expected number of failures with respect to time as follows:
The intensity function is also referred to as the renewal rate, failure intensity or the rate of occurrences of failure. It is an absolute rate of failure for repairable systems. If the intensity function is decreasing, the system is improving and if intensity function is increasing, the system is deteriorating. If the intensity function is not changing with time, the process reduces to HPP. From intensity function, the expected number of failures can be estimated as follows:

\[
E[N(t)] = \int_0^t \rho(t') \, dt'
\]  

(4.3)

An instantaneous MTBF is given by,

\[
MTBF = \frac{1}{\rho(t)}
\]  

(4.4)

An interval MTBF is given by,

\[
MTBF(t_1, t_2) = \frac{t_2 - t_1}{m(t_1, t_2)}
\]  

(4.5)

\[
m(t_1, t_2) = E[N(t_2) - (N(t_1))] = \int_{t_1}^{t_2} \rho(t) \, dt
\]  

(4.6)

Two popular parameterizations for the intensity function of an NHPP are the power law intensity (Weibull intensity) and the log-linear intensity. Several practical examples reviewed show that the power law process is preferred, due to its similarities with the Weibull distribution fitting methods. The intensity function is of the same form of the failure rate of a Weibull distribution. In case of Weibull intensity function, we get the expression for the expected number of failures in an interval (0, t), of a component subjected to minimal repair as follows:

\[
E[N(t)] = \int_0^t \rho(t') \, dt' = \int_0^t \beta_i \left(\frac{t}{\eta_i}\right)^{\beta_i - 1} \, \left(\frac{t}{\eta_i}\right)^{\beta_i} \, dt = \left(\frac{t}{\eta_i}\right)^{\beta_i}
\]  

(4.7)

Use of an NHPP is a two stage problem, the first relates to the fitting of an intensity function to data and the second uses the cumulative intensity function to estimate reliability for the system. When trends are not present and data can be assumed to be iid,
only one stage is needed, where directly a time-to-failure distribution is fitted to data and reliability estimates are obtained from it. Figure 4.2 shows the procedure for estimating maintenance and repair cost based on proper selection of time-to-failure model that correctly describes the failure process of a given component. Using this method, whether to plan for a renewal approach or minimal repair for a given component/product can be decided. In the absence of system ageing or reliability growth, the renewal process approach can be used to estimate the maintenance and repair costs. But, whenever system ageing or reliability growth is observed with time, the minimal repair process approach should be employed to estimate the maintenance and repair costs.

![Diagram of Methodology for planning renewal or minimal repair approach](image)

**Figure 4.2 Methodology for planning renewal or minimal repair approach**
4.5 Model formulation

The mathematical equations to estimate individual cost components of the proposed model have been formulated for repairable systems. The most general comprehensive life cycle cost model for a repairable system represented by Eq. (3.1) can be reduced to:

\[ \text{LCC}_{\text{rp}} = C_p + C_{ic} + C_o + C_{mrs} + C_d \]  (4.8)

In this generalized model, five key phases in the life cycle of a repairable system such as acquisition, installation and commissioning, operation, maintenance and repair and disposal are considered. The equations to estimate the individual cost components have been formulated in consultation with industry based on the characteristics of repairable systems. The stochastic point processes approach is applied in modelling the maintenance and repair costs. The methodology adopted and the equations formulated are presented in the following sections.

4.5.1 Acquisition cost

The acquisition cost accounts for the cost of concept and definition (\(C_1\)), research and development (\(C_2\)), design and development (\(C_3\)), product validation (\(C_4\)), intellectual property (\(C_5\)), raw material (\(C_6\)), inspection and storage (\(C_7\)), manufacturing (\(C_8\)), recurring functional testing (\(C_9\)), assembly (\(C_{10}\)), diagnosis and rework (\(C_{11}\)), quality control (\(C_{12}\)), qualification and certification (\(C_{13}\)), profit charged by manufacturer (\(C_{14}\)), packaging and warehousing (\(C_{15}\)), transportation and distribution (\(C_{16}\)), training and documentation (\(C_{17}\)), product modification (\(C_{18}\)) and warranty cost (\(C_{19}\)) etc. The acquisition cost (\(C_p\)) can be expressed as follows:

\[ C_p = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 + C_8 + C_9 + C_{10} + C_{11} + C_{12} + C_{13} + C_{14} + C_{15} + C_{16} + C_{17} + C_{18} + C_{19} \]  (4.9)

The acquisition cost is the easily identifiable element in the life cycle of any product or a system. The work related to estimation of product acquisition cost is abundant in literature. A large number of efforts are there to model the production/construction phase of a product life cycle. A number of such efforts to estimate product acquisition cost are discussed in chapter 2. In this model, the acquisition cost is estimated as the sum of the
costs of different elements as given in Eq. (4.9). A method to estimate such individual
cost components using activity based costing approach is presented in chapter 8.

4.5.2 Installation and commissioning cost

The equation to estimate installation and commissioning cost can be formulated
using activity based costing method. In this method, all the activities associated with the
installation and commissioning of a system can be identified along with the time
consumed by each activity and the man power needed to perform the given activity. The
cost of tooling required for each activity can also be identified. Mathematically, the
installation and commissioning cost can be estimated as follows:

\[ C_{ic} = \sum_{i=1}^{n_{icl}} [(T_{icl}, N_{icl}, C_{icl}) + Ct_{icl}] \]  \hspace{1cm} (4.10)

4.5.3 Operation cost

Two main cost drivers associated with the operation of a repairable system, the
cost of energy and labour cost of operation have been identified. Considering these two
factors the following equation is developed to estimate the operation cost of a system.
Mathematically, the system operation cost can be estimated as follows:

\[ C_o = t \cdot [C_{eh}(kw) + C_{lh}] \]  \hspace{1cm} (4.11)

4.5.4 Maintenance and repair cost

The maintenance and repair cost is estimated as the sum of the costs of
preventive and corrective maintenance. The cost of preventive maintenance is estimated
as the sum of the cost of the components to be replaced during the preventive
maintenance, the labour cost and the fixed support cost associated with the preventive
maintenance. The fixed support cost covers the cost of tooling and the cost of
documentation needed in preventive maintenance. The corrective maintenance costs are
estimated based on the expected number of failures in a given time interval. The costs
are evaluated for two different after repair states mainly as-good-as-new (renewal
process) and as-bad-as-old (minimal repair process). The suggested methodology is
believed to be a simple way for system designers and maintenance analysts to assess the
costs associated with the system failures and to discriminate whether a renewal approach
or minimal repair approach should be used to represent them. The proposed modelling methodology is based upon following assumptions.

- The component life time is modelled using a two parameter Weibull distribution.
- The number of replacements of the components in an interval (0, t) follow renewal process in the first case.
- The number of replacements of the components in an interval (0, t) follow minimal repair process in the second case.

The expected maintenance and repair cost over the life of a repairable system for system renewal after each failure (as-good-as-new) can be estimated as follows:

\[
C_{mr} = \frac{t}{t_0} \left( \sum_{i=1}^{i=m} C_i \cdot F_{pi} + N_p \left[ \frac{\sum_{i=1}^{k} (T_{mpi} \cdot F_{pti})}{\sum_{i=1}^{k} F_{pti}} \right] C_{pi} + C_f \right) \\
+ \sum_{i=1}^{i=n-m} \left( \frac{t}{\eta_i \cdot \Gamma(1 + \frac{1}{\beta_i})} \right) \cdot [C_i + MTTR_i \cdot C_{ri}] 
\] (4.12)

The expected maintenance and repair cost over the life of a repairable system for minimal repair after each failure (as-bad-as-old) can be estimated as follows:

\[
C'_{mr} = \frac{t}{t_0} \left( \sum_{i=1}^{i=m} C_i \cdot F_{pi} + N_p \left[ \frac{\sum_{i=1}^{k} (T_{mpi} \cdot F_{pti})}{\sum_{i=1}^{k} F_{pti}} \right] C_{pi} + C_f \right) \\
+ \sum_{i=1}^{i=n-m} \left( \frac{t \cdot \beta_i}{\eta_i} \right) \cdot [C_i + MTTR_i \cdot C_{ri}] 
\] (4.13)

The methodology is believed to be generalized one in another aspect also as it can model most of the system failure rates as the failure rate function is of the Weibull form. By varying the shape parameter \( \beta \), a number of failure rate functions can be obtained.

\subsection*{4.5.5 Disposal cost}

The system disposal strategy can be recycling, reusing or disposing off the individual components of the system. The five different cost drivers involved in system recycling are retrieval, separation, identification, reprocessing and remarketing (Ishii et al. 1994). The system recycling cost is also estimated as the sum of cost of disassembly, cost of shredding, cost of material recovery and cost of dumping (Chen et al. 1993). In this model, the system disposal cost is estimated as sum of the cost of disassembly \( C_{DA} \),
cost of recovering a part of the material (\(C_R\)) and cost of dumping (\(C_{DU}\)) the remaining material. The disassembly cost is estimated as product of the time required to disassemble the system and the cost incurred per unit time. The model considers the cost gain due to material recovery and the transportation cost associated with the recovered material. The cost of disposing the material is estimated as product of the weight of the material to be dumped and the cost of dumping. Mathematically, the system disposal cost can be estimated as follows:

\[
C_d = C_{DA} + C_R + C_{DU}
\]  

\[
C_d = \left\{ C_{dah} \sum_{i=1}^{i=n} T_i \right\} + \left[ (C_{tr} \cdot km \cdot W_r) - (C_s \cdot W_r) \right] + \left[ (C_{tdu} \cdot km1 \cdot W_{du}) \right]
\]  

\[
+ (C_{du} \cdot W_{du}) \right\}
\]

\[4.14\]

\[4.15\]

4.5.6 Life cycle cost

As stated earlier, the system life cycle cost is sum of all the cost components as formulated above. Mathematically, the repairable system life cycle cost for system renewal after each failure (as-good-as-new) can be expressed by adding equations (4.9), (4.10), (4.11), (4.12) and (4.15) as follows:

\[
LCC_r = C_p + \sum_{i=1}^{i=n} \left[ (T_{icr} + N_{icr} \cdot C_{icr} + C_{t icr}) \right] + t \cdot [C_{eh} (kw) + C_{th}]
\]

\[+ \frac{t}{t_0} \left\{ \sum_{i=1}^{i=m} C_i \cdot F_{pi} + N_p \left[ \frac{\sum_{i=k}^{i=m} (T_{mpt} \cdot F_{pti})}{\sum_{i=1}^{i=k} F_{pti}} \right] C_{p1} + C_f \right\}
\]

\[+ \sum_{i=1}^{i=n-m} \left[ \frac{t}{\eta_i \cdot \Gamma \left( 1 + \frac{1}{\beta_i} \right)} \right] \cdot [C_i + MTTR_{ri} \cdot C_{ri}]
\]

\[+ \left\{ C_{dah} \sum_{i=1}^{i=n} T_i \right\} + \left[ (C_{tr} \cdot km \cdot W_r) - (C_s \cdot W_r) \right] + \left[ (C_{tdu} \cdot km1 \cdot W_{du}) \right]
\]

\[+ (C_{du} \cdot W_{du}) \right\}
\]

\[4.16\]
Mathematically, the repairable system life cycle cost for minimal repair after each failure (as-bad-as-old) can be expressed by adding equations (4.9), (4.10), (4.11), (4.13) and (4.15) as follows:

\[
LCC' = C_p + \sum_{i=1}^{i=n} \left[ (T_{cli} \cdot N_{cli} \cdot C_{cli}) + C_{tcli} \right] + \frac{t}{t_0} \left\{ \sum_{i=1}^{i=m} C_i \cdot F_{pi} + N_p \left[ \frac{\sum_{i=1}^{i=k} (T_{mpi} \cdot F_{pti})}{\sum_{i=1}^{i=k} F_{pti}} \right] C_{p1} + C_f \right\}
+ \sum_{i=1}^{i=n-m} \left( \frac{t}{\eta_i} \right)^{\beta_i} C_i + MTTR_i \cdot C_{rti}
+ \left\{ \left[ C_{dah} \cdot \sum_{i=1}^{i=n} T_i \right] + [(C_{tr} \cdot km. W_r) - (C_s . W_r)] + [(C_{tdu} \cdot km1 . W_{du})
+ (C_{du}. W_{du}) \right\}
\]

(4.17)

4.6 Case study – a pump from industry

The developed generalized model is validated using the data for a typical repairable system, a pump (Single Stage, Horizontal, Split-Case Type) manufactured by a well-known pump manufacturer in India. The data related to the cost, failures and maintenance in regard to the pump under study was obtained from the pump manufacturer. The pump specifications are as given below.

4.6.1 Pump specifications

- Pump initial price – Rs 130000
- Motor cost – Rs 75000
- (110 KW, 415V, 4 Pole, TEFC motor)
- Cost of coupling – Rs 1500
- Cost of base frame – Rs 10000
- Design life of the pump – 70000 hours
- Pump efficiency – 76%
- Motor efficiency – 92%
- Head – 90 m
- Flow rate – 300 m³/hr
- Annual operating requirement – 7000 hours
4.6.2 Pump acquisition cost

The pump set consists of a pump, motor, coupling and base frame. The data in regard to acquisition cost of pump, motor, coupling and base frame is directly obtained from the pump manufacturer. Using this data, the acquisition cost is calculated as follows:

\[ C_{pp} = \text{Cost of Pump} + \text{Cost of Motor} + \text{Cost of Base Frame} + \text{Cost of Coupling} \]

\[ C_{pp} = 130000 + 75000 + 10000 + 1500 = \text{Rs 216500} \quad (4.18) \]

4.6.3 Pump installation and commissioning cost

The installation and commissioning task is subdivided into seven different activities such as preparing the foundation, grouting, pump set alignment before piping, piping, pump set alignment after piping, electric connections and commissioning. Table 4.1 shows the activities and the related data collected such as time consumed by each activity, number of persons required, labour and tooling cost associated with each activity.

<table>
<thead>
<tr>
<th>Activity</th>
<th>( T_{icl} )</th>
<th>( N_{icl} )</th>
<th>( C_{icl} )</th>
<th>( T_{icl} \cdot N_{icl} \cdot C_{icl} )</th>
<th>( C_{ticl} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preparing foundation</td>
<td>4</td>
<td>3</td>
<td>300</td>
<td>3600</td>
<td>500</td>
</tr>
<tr>
<td>Grouting</td>
<td>8</td>
<td>3</td>
<td>300</td>
<td>7200</td>
<td>1000</td>
</tr>
<tr>
<td>Pump set alignment</td>
<td>1</td>
<td>3</td>
<td>300</td>
<td>900</td>
<td>500</td>
</tr>
<tr>
<td>Piping</td>
<td>2</td>
<td>3</td>
<td>300</td>
<td>1800</td>
<td>500</td>
</tr>
<tr>
<td>Pump set alignment</td>
<td>1</td>
<td>3</td>
<td>300</td>
<td>900</td>
<td>500</td>
</tr>
<tr>
<td>Electric connections</td>
<td>4</td>
<td>3</td>
<td>300</td>
<td>3600</td>
<td>1000</td>
</tr>
<tr>
<td>Commissioning</td>
<td>8</td>
<td>1</td>
<td>900</td>
<td>7200</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>25200</strong></td>
<td><strong>4000</strong></td>
</tr>
</tbody>
</table>

Using equation (4.10) the installation and commissioning cost is calculated as follows:

\[ C_{icp} = 25200 + 4000 = \text{Rs 29200} \quad (4.19) \]

4.6.4 Pump operation cost

The pump operation cost is estimated using following data.

- Pump design life = 70000 hours
- Cost of energy = Rs 5/kWH
- Labour cost of operation = Rs 50 per hour
- Pump efficiency – 76%
- Motor efficiency – 92%
- Head – 90 m
- Flow rate – 300 m³/hr
Using Eq. (4.11) the operation cost is calculated as follows:

\[ C_{op} = 70000 \left[ 5 \left( \frac{300 \times 90}{366 \times 0.76 \times 0.92} \right) + 50 \right] = \text{Rs 40427400} \quad (4.20) \]

### 4.6.5 Pump maintenance and repair cost

As stated earlier the maintenance and repair cost includes the cost of preventive maintenance and cost of corrective maintenance. Table 4.2 shows the data required to estimate cost of preventive maintenance.

**Table 4.2 Preventive maintenance cost calculation**

<table>
<thead>
<tr>
<th>Component</th>
<th>( C_i ) (Rs)</th>
<th>( F_{pi} ) (per year)</th>
<th>( T_{mpi} ) (hr)</th>
<th>( F_{pti} ) (per hour)</th>
<th>( C_i \cdot F_{pi} )</th>
<th>( T_{mpi} \cdot F_{pti} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wear ring</td>
<td>800</td>
<td>1</td>
<td>4</td>
<td>0.00014</td>
<td>800</td>
<td>0.00056</td>
</tr>
<tr>
<td>Shoulder ring</td>
<td>1000</td>
<td>1</td>
<td>2</td>
<td>0.00014</td>
<td>1000</td>
<td>0.00028</td>
</tr>
<tr>
<td>Mechanical seal</td>
<td>1200</td>
<td>0.5</td>
<td>4</td>
<td>0.000071</td>
<td>600</td>
<td>0.000284</td>
</tr>
<tr>
<td>Bearing</td>
<td>6000</td>
<td>0.5</td>
<td>4</td>
<td>0.000071</td>
<td>3000</td>
<td>0.000284</td>
</tr>
<tr>
<td>Angular contact bearing</td>
<td>10000</td>
<td>0.5</td>
<td>4</td>
<td>0.000071</td>
<td>5000</td>
<td>0.000284</td>
</tr>
<tr>
<td>Oil seal</td>
<td>1000</td>
<td>2</td>
<td>2</td>
<td>0.00028</td>
<td>2000</td>
<td>0.00056</td>
</tr>
<tr>
<td>O ring for insert</td>
<td>1500</td>
<td>2</td>
<td>2</td>
<td>0.00028</td>
<td>3000</td>
<td>0.00056</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00105</td>
</tr>
</tbody>
</table>

The preventive maintenance cost per year assuming \( N_p = 3 \), \( C_{pi} = \text{Rs 5000} \) per hour and \( C_f = \text{Rs 3000} \), is calculated as follows:

\[
C_{pmp} = \left\{ \sum_{i=1}^{m} C_i \cdot F_{pi} + N_p \left[ \frac{\sum_{i=1}^{k} T_{mpi} \cdot F_{pti}}{\sum_{i=1}^{k} F_{pti}} \right] \right\} C_{pi} + C_f \quad (4.21)
\]

\[
C_{pmp} = \left\{ 15400 + 3 \left[ \frac{0.00282}{0.00105} \right] \right\} \text{Rs 5000} \quad (4.22)
\]

\[ C_{pmp} = \text{Rs 58700} \]

Table 4.3 shows the data required to estimate corrective maintenance costs. The corrective maintenance cost for the impeller used in the pump as an example can be estimated as follows:

The mean time between failures is estimated as follows:

\[ \text{MTBF}_i = \eta_i \Gamma \left( 1 + \frac{1}{\beta_i} \right) \quad (4.23) \]
MTBF_I = \frac{35000 \cdot \Gamma \left(1 + \frac{1}{2.5}\right)}{2.5} = 31054 \text{ hrs}

Using Eq. (4.1) the expected number of failures for the renewal process are estimated as follows:

\[ E[N(t)]_I = \left(\frac{t}{MTBF_I}\right) = \left(\frac{70000}{31054}\right) = 2.25 \tag{4.24} \]

Using Eq. (4.7) the expected number of failures for minimal repair process are estimated as follows:

\[ E'[N(t)]_I = \left(\frac{t}{\eta_I}\right)^{-\frac{1}{\beta_I}} = \left(\frac{70000}{31054}\right)^{-\frac{1}{2.5}} = 5.65 \tag{4.25} \]

The cost per failure (assuming the activity cost per corrective maintenance action as Rs 5000 per hour) is estimated as follows:

\[ C_{F_I} = [C_I + MTTR_I \cdot C_{rI}] \tag{4.26} \]

\[ C_{F_I} = [20000 + 8.5000] = \text{Rs 60000} \]

The maintenance and repair cost for impeller for renewal after each failure is estimated as follows:

\[ C[N(t)]_I = E[N(t)]_I \cdot C_{F_I} \tag{4.27} \]

\[ C[N(t)]_I = 2.25 \times 60000 = \text{Rs 135000} \]

The maintenance and repair cost for impeller for minimal repair after each failure is estimated as follows:

\[ C'[N(t)]_I = E'[N(t)]_I \cdot C_{F_I} \tag{4.28} \]

\[ C'[N(t)]_I = 5.65 \times 60000 = \text{Rs 339000} \]
Table 4.3 Corrective maintenance cost calculation

| Component          | $C_i$ (Rs) | $\beta_i$ | $\eta_i$ (hrs) | MTBF$_i$ (hrs) | MTTR$_i$ (hrs) | $E_i[N(t)]$ | $E'_i[N(t)]$ | $CF_i$ (Rs) | $C_i[N(t)]$ (Rs) | $C'_i[N(t)]$ (Rs) |
|--------------------|------------|-----------|----------------|----------------|----------------|-------------|-------------|------------|----------------|----------------|----------------|
| LH casing          | 40000      | 1.3       | 87600          | 80712          | 8              | 0.86        | 0.74        | 80000      | 68800          | 59200          |
| UH casing          | 25000      | 1.3       | 87600          | 80712          | 4              | 0.86        | 0.74        | 45000      | 38700          | 33300          |
| Impeller           | 20000      | 2.5       | 35000          | 31054          | 8              | 2.25        | 5.65        | 60000      | 135000         | 339000         |
| Shaft              | 18000      | 1.2       | 70000          | 65778          | 8              | 1.06        | 1           | 58000      | 61500          | 58000          |
| Impeller key       | 6000       | 1.5       | 35000          | 31556          | 8              | 2.21        | 2.82        | 46000      | 101650         | 129700         |
| Key for coupling   | 6000       | 1.5       | 70000          | 63112          | 4              | 1.1         | 1           | 26000      | 28600          | 26000          |
| Impeller nut       | 4000       | 1.3       | 35000          | 32245          | 8              | 2.17        | 2.46        | 44000      | 95500          | 108250         |
| Bearing lock nut   | 8000       | 1.3       | 50000          | 46065          | 4              | 1.51        | 1.54        | 28000      | 42250          | 43100          |
| Vent valve         | 20000      | 1.4       | 70000          | 63737          | 4              | 1.09        | 1           | 40000      | 43600          | 40000          |
| Insert             | 10000      | 1.2       | 46500          | 43695          | 4              | 1.6         | 1.63        | 30000      | 48000          | 48900          |
| Motor              | 75000      | 1.2       | 35000          | 32889          | 8              | 2.12        | 2.29        | 115000     | 243800         | 263350         |
| Coupling           | 1500       | 2.0       | 70000          | 62036          | 4              | 1.12        | 1           | 21500      | 24100          | 21500          |
| Base frame         | 10000      | 1.2       | 70000          | 65778          | 8              | 1.06        | 1           | 50000      | 53000          | 50000          |
| **Total**          |            |           |                |                |                |             |             |            | 984500         | 1220300        |
The expected maintenance and repair cost over the life of the pump for pump renewal after each failure (as-good-as-new) can be estimated using Eq. (4.12) as follows:

\[
C_{mrp} = \frac{70000}{7000} \left( 15400 + 3 \left( \frac{0.00282}{0.00105} \right) \left( 5000 + 3000 \right) \right) + 984500
\]

\[
C_{mr} = \text{Rs 1571350} \quad (4.29)
\]

The expected maintenance and repair cost over the life of the pump for minimal repair after each failure (as-bad-as-old) can be estimated using Eq. (4.13) as follows:

\[
C'_{mrp} = \frac{70000}{7000} \left( 15400 + 3 \left( \frac{0.00282}{0.00105} \right) \left( 5000 + 3000 \right) \right) + 1220300
\]

\[
C'_{mr} = \text{Rs 1807150} \quad (4.30)
\]

4.6.6 Pump disposal cost

The data to estimate the pump disposal cost is given below.

- Weight of the pump set = 515 kg
- Material to be recovered = 490 kg
- Material to be disposed = 25 kg
- Distance over which the recovered material to be transported = 100 km (assumed)
- Distance over which the dumped material to be transported = 1 km (at pump site)
- Cost of transportation = Rs 100/ton/km
- Scrap rate = Rs 25/kg
- Cost of dumping = Rs 1000/ton
- Time required to disassemble the pump = 8 hours
- Hourly disassembly cost = Rs 150

Using equation (4.15) the disposal cost is calculated as follows:

\[
C_{dp} = \text{Rs } - \ 6100 \quad (4.31)
\]
4.6.7 Pump life cycle cost

The pump life cycle cost is the sum of all the cost components estimated as above. The pump life cycle cost for pump renewal after each failure (as-good-as-new) can be expressed by adding the values obtained using equations (4.18), (4.19), (4.20), (4.29) and (4.31) as follows:

\[ LCC_p = 216500 + 29200 + 40427400 + 1571350 + (−6100) = Rs \, 42238350 \]

The life cycle cost for minimal repair of pump after each failure (as-bad-as-old) can be expressed by adding the values obtained using equations (4.18), (4.19), (4.20), (4.30) and (4.31) as follows:

\[ LCC'_p = 216500 + 29200 + 40427400 + 1807150 + (−6100) = Rs \, 42474150 \]

4.6.8 Present value of life cycle cost

In life cycle cost analysis, some of the cost elements will be incurred at the outset and others may be incurred at different times throughout the life of the pump. It is therefore essential to calculate the present value of the life cycle cost. Present value is the value on a given date of a future payment or series of future payments, discounted to reflect the time value of money and other factors such as investment risk. Present value calculations are widely used in business and economics to provide a means to compare cash flows at different times on a meaningful basis. The present value (PV) of a future value (FV) can be computed as follows:

\[ PV = \frac{FV}{(1 + i)^p} \]  

(4.32)

Where, \( i \) is the rate at which the amount will be compounded each period and \( p \) is the number of periods. Using Eq. (4.32) the PV of life cycle cost for renewal process and minimal repair process with an interest rate of 8% and over a period of ten years is estimated as follows:

For renewal process:

\[ PV = \frac{42238350}{(1 + 0.08)^{10}} = Rs \, 19564528 \]

For minimal repair process:

\[ PV = \frac{42474150}{(1 + 0.08)^{10}} = Rs \, 19673750 \]
4.7 Life cycle cost results

Table 4.4 shows the results obtained for LCC of the pump while Figure 4.3 compares the LCC components for renewal process and minimal repair process. The pump operation cost is 95% and maintenance and repair cost is 3.72% of the total pump life cycle cost for renewal assumption and 4.42% for minimal repair assumption. Thus, the operation and maintenance costs dominated the pump LCC. The pump acquisition cost is only 0.5% of pump LCC. The installation and commissioning cost is significantly low. The pump has life cycle cost of Rs 279 per hour of pump operation for renewal assumption and Rs 281 per hour of pump operation for minimal repair assumption based on PV. This can be used as a comparison factor to evaluate different design alternatives.

**Table 4.4 Results of life cycle cost analysis**

<table>
<thead>
<tr>
<th>Cost component</th>
<th>Contribution to LCC (Rs)</th>
<th>% of LCC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Renewal process</td>
<td>Minimal repair process</td>
</tr>
<tr>
<td>Pump initial cost</td>
<td>216500</td>
<td>216500</td>
</tr>
<tr>
<td>Installation and commissioning</td>
<td>29200</td>
<td>29200</td>
</tr>
<tr>
<td>Operation</td>
<td>40427400</td>
<td>40427400</td>
</tr>
<tr>
<td>Maintenance and repairs</td>
<td>1571350</td>
<td>1807150</td>
</tr>
<tr>
<td>Disposal</td>
<td>-6100</td>
<td>-6100</td>
</tr>
<tr>
<td>Life cycle cost</td>
<td>42238350</td>
<td>42474150</td>
</tr>
<tr>
<td>PV of life cycle cost (Rs)</td>
<td>19564528</td>
<td>19673750</td>
</tr>
<tr>
<td><strong>Life cycle cost per hour (Rs)</strong></td>
<td><strong>279</strong></td>
<td><strong>281</strong></td>
</tr>
</tbody>
</table>

**Figure 4.3 Comparison of life cycle cost components for pump**
4.8 Conclusions

A comprehensive generalized life cycle cost model for repairable systems based on reliability (R) and maintainability (M) aspects has been proposed and the technique has been illustrated through a specific application, namely an industrial pump. The model is comprehensive in that it considers several aspects of product’s life cycle. Necessary equations have been formulated for the cost components of the model for a repairable system. The repairable system life-time is modelled using a two parameter Weibull distribution. To model maintenance and repair costs stochastic point process approach is employed. Based on expected number of failures the costs are evaluated for two different after repair states mainly as-good-as-new (renewal process) and as-bad-as-old (minimal repair process). The developed model has been applied to a typical repairable system, a pump set manufactured by a well known pump manufacturer in India and the results obtained are discussed. Based on the analysis and the example presented above following conclusions are drawn:

- The life cycle energy and maintenance and repair costs dominated the pump life cycle cost.
- The pump operation cost is observed to be 95% of pump LCC.
- For renewal process, the maintenance and repair cost is 3.72% of pump LCC while for minimal repair process it is 4.42% of pump LCC.
- Highest maintenance and repair cost is observed for minimal repair process which is 15% more than the cost observed for renewal process.
- The pump initial cost is only a fraction of its life cycle cost.

It is known that the power consumed depends on the energy lost in inefficient motors/bearings, and energy lost in pump dynamics. Thus, use of high efficiency motors and high efficiency pump internals can considerably save the total power costs. The system maintenance and repair cost depends on the expected number of failures observed over the design life of a system. The expected number of failures depends on the system design life, the characteristic life $\eta$ and the shape parameter $\beta$ of the component failure distributions. Therefore, due consideration to these parameters at system design stage will reduce maintenance and repair costs and ultimately the life cycle cost considerably. The pump disposal cost may vary from region to region as the parameters in the equation of disposal cost vary region wise. The data used in this paper is for an industrial pump, but the suggested method can be applied to any other repairable system. Thus, it is a general model applicable to any repairable system.