A methodology for design for warranty with focus on reliability and warranty policies

Prashant M. Ambad and Makarand S. Kulkarni
Mechanical Engineering Department, Indian Institute of Technology Delhi, New Delhi, India

Abstract

Purpose – The purpose of the paper is to develop a conceptual framework that integrates the technology and commercial issues early at the design stage to minimize warranty costs in the most effective and efficient manner and also to develop a model for optimization of warranty with specific focus on reliability and warranty policies.

Design/methodology/approach – The critical issues in warranty are addressed which affect the warranty cost. An optimization model to achieve multiple goals like minimization of the warranty cost and improving the reliability of the product is developed using genetic algorithm as a solution methodology. The model is illustrated with a real case of automobile engine.

Findings – The results of the optimization show improvement in mean time between failures (MTBF) which results due to improvement in the product reliability and also the targeted warranty cost is achieved.

Research limitations/implications – The model developed needs to be further extended with inclusion of additional decision variable such as support level offered and more objectives such as attractiveness of the warranty from the customer’s view point and spares cost to the customer.

Originality/value – The paper provides the help to the designers at the design stage to take the decisions related to warranty in deciding the warranty parameters.

Keywords Warranty policies, Reliability, Mean time between failures, Warranty optimization, Warranty cost, Genetic algorithms

Paper type Research paper

1. Introduction

The complexity of the products in the recent past has increased significantly to meet the ever increasing needs and expectations of consumers. In the purchase decision of a product, buyers typically compare characteristics of comparable models of different brands available in the market. When competing brands are nearly identical, it is very difficult, in many instances, to choose a particular product solely on the basis of the product-related characteristics such as price, features, product quality, finance offered by the manufacturer, and so on. In such situations, post-sale factors – warranty, support level, maintenance, spare parts cost and their availability, etc., are important in the choice of the product. Of these, warranty is a one of the most influential factors that is known to the buyer at the time of purchase.

A failure can occur early in an item's life due to manufacturing defects or at a later time in its life due to degradation which is dependent on age and usage. Consumers need assurance that the product they purchase will be able to carry out its intended function over a period of time and protected against product failures in the early phases of product usage. Manufacturers provide the protection by offering warranty.

A warranty is a contract between the buyer and the manufacturer associated with the sale of a product. Warranty typically specifies the performance that is to be
expected from the product, conditions of use and the rectification available to the buyer in case if failure occurs.

A warranty of any type, since it involves an additional service associated with a product, will lead to potential costs to the manufacturer beyond those associated with the design, manufacture and sale of the product. The warranty servicing costs may vary from 2 to 10 percent of sale price depending on the product and the manufacturer (Murthy, 2007). The warranty cost strongly depends on the reliability of the product which in turn depends upon several factors, some of which are controlled by the manufacturer, such as the decisions made during the design and development stage. Some of the factors are related to the consumer such as the product usage pattern and the operating environment and maintenance.

To address the issues related to warranty, there is a need to develop a framework which addresses the critical parameters which affect the decisions related to warranty and integrate the issues in such a way that the warranty cost can be minimized.

In the present study, a warranty optimization model is developed considering multiple target goals like:

1. limiting the warranty cost to a certain proportion of the engine price; and
2. improving the mean time between failures (MTBF) to a certain proportion as compared to existing one in order to improve the reliability of the engine.

The decision variables considered are component alternatives, type of warranty policy and warranty duration. The model is demonstrated using a case study of an engine manufacturer. The optimization is carried out using genetic algorithm (GA) approach.

The outline of the paper is as follows. Section 2 reviews the literature related to the parameters affecting warranty cost and warranty optimization, Section 3 proposes a conceptual framework that links warranty parameters and warranty cost. In Section 4, a warranty optimization model is developed. Finally, paper concludes with remarks in Section 5.

2. Literature review
Depending upon the type of product, an appropriate warranty policy needs to be selected. A lot of research has been carried on for selection of an appropriate warranty policy and warranty length by considering either the manufacturer’s or the buyer’s point of view. Offering an attractive warranty policy is typically costly, especially for products that deteriorate quickly.

Blischke and Murthy (1992) have proposed a taxonomy for warranty policies for new products and grouped these policies into number of categories. Murthy and Chattopadhyay (1999) have developed policies and taxonomy for second hand products. Murthy and Blischke (2006) have discussed in detail about the warranty polices and the associated warranty cost analysis. Over the last decade, manufacturers have started offering extended warranty which provides the customer with additional protection beyond the normal warranty at an additional cost. The popularity of extended warranty has resulted in third parties providing these services.

Reliability of a product conveys the concept of dependability, successful operation or performance and the absence of failures. Failures over the warranty period are closely linked to product reliability. The reliability of a product gets determined by the decisions made during the pre-production stages (frontend, design and development) as well as the production stage of the product life cycle (Blischke and Murthy, 2000). Murthy et al. (2008, 2009) have dealt with reliability decision making during the
front-end (or feasibility) and the design and development stages of new product development. Murthy (2007) has given a brief overview of reliability as well as warranty and discussed some new issues and the challenges for future research. Doganaksoy et al. (2006) have described methods of implementing quality control techniques for various processes in business enterprises and to improve reliability of equipment, based on analysis of data pertaining to warranty.

Preventive maintenance (PM) over the warranty period has a greater impact on the warranty servicing cost. It is worthwhile to carry out maintenance as it affects the overall health of the product in future. Murthy and Jack (2003) have reviewed the literature pertaining to warranty and maintenance and suggested areas for future research. Park and Pham (2012) developed warranty cost models considering a periodic PM policy with both corrective maintenance and PM and also determines three decision variables including warranty period, repair time limit and periodic maintenance cycles. Huang and Yen (2009) have developed a two-dimensional warranty model in which the customer is expected to perform appropriate PM. The warranty policy that maximizes the manufacturers’ profits is determined. Ben-Daya and Noman (2006) have developed an integrated model that simultaneously considers inventory production decisions, PM schedule and warranty policy for a deteriorating system that experiences shifts leading to an out of control state. Jung and Park (2003) have developed an approach for optimal periodic PM policies following the expiration of warranty by minimizing the expected long-run maintenance cost per unit time. Djamaludin et al. (2001) have developed a framework to study warranty and maintenance. Kim et al. (2004) have proposed a model to determine discrete time instants when PM actions are to be carried out over the warranty period.

Warranty logistics deals with various issues relating to the servicing of warranty. Proper management of warranty logistics is needed not only to reduce the warranty servicing cost but also to ensure customer satisfaction. Diaz et al. (2012) addressed the problem of improving warranty management programs through logistic support planning and presented a framework for the military industry in which logistic support strategies are widely applied. Murthy et al. (2004) have linked the literature on warranty and on logistics and then discussed the different issues in warranty logistics. Blanchard et al. (1995) have dealt with maintenance management and Blanchard (1998) with some related logistical issues. Loomba (1996) discussed the linkage between product distribution and service support channels.

In the literature, the optimization of warranty is carried out in which objective functions for optimization are the minimization of the expected warranty cost and price, maximization of the expected profit per product and market share, improvement of reliability (Mitra and Patankar, 1988, 1997; Yun, 1997; Liu et al., 2006; Lu and Chiang, 2008; Wu et al., 2009; Saidi-Mehrabad et al., 2010; Shafiee et al., 2011; Shafiee and Zuo, 2011; Park and Pham, 2012; Faridimehr and Niaki, 2012). The most commonly used constraints in the literature are related to warranty reserves and life cycle costs (Kleyner and Sandborn, 2008; Mitra and Patankar, 1990; Painton and Campbell, 1995). The decision variables typically used are type and duration of the warranty policy, reliability of the product and selling price (Mohan et al., 2009; Wang et al., 2010; Huang et al., 2007; Rai and Singh, 2005; Chun and Tang, 1999; Blischke and Vij, 1996).

Goal programming has been used by a number of authors in the literature to solve the single as well as multi objective problems (Mahdavi et al., 2009; Javadi et al., 2008). Different meta-heuristic methods like GA, simulated annealing are used as solution techniques for solving the optimization problems. Monga and Zuo (1998) presented a
study on reliability based design of a series-parallel system and used GA to obtain optimal values of system design, burn-in period for different lengths of warranty, PM intervals and replacement time. Deb (1999, 2001) and Hu et al. (2007) used multi-objective GA to solve the goal programming problems.

Some of the literature also focussed on achieving customer satisfaction through improvements in the warranty parameters by making changes in the design. Manna et al. (2006) and Maronick (2007) focussed on maximization of customer’s utility in terms of warranty duration for the different warranty policies. Researchers also focussed on determination of the customer’s satisfaction in terms of warranty claims after making improvements in the design (Majeske and Herrin, 1998; Yang and Zaghati, 2002; Jack and Murthy, 2004; Lassar et al., 1998). Price and Dawar (2002) and Noll (2004) have examined warranty as a signal for quality and studied its impact from the customer’s perspective.

As can be seen from the above review, minimization of warranty cost is a multidimensional problem. It is studied either as a single objective or multi-objective optimization problem. In addition to this, the complexity of the problem is very high due to the way in which these parameters affect warranty cost.

In the next section, we present a conceptual framework for modeling the impact of some of the most important parameters discussed in the present section on the warranty cost and eventually on profits. Subsequently, a warranty optimization model is also developed with specific focus on reliability and warranty polices.

3. The proposed conceptual framework

From the business perspective, there can be multiple goals such as market share, total profits, etc. Warranties not only impact total sales in a positive manner, but also impact warranty cost and profit margin. Figure 1 shows the link between warranty parameters and warranty cost.

As shown in Figure 1, four decisions namely warranty policy, product reliability, maintenance and warranty logistics are important from warranty point of view. The warranty policy related decisions decide the type and duration of warranty.

![Conceptual framework](image-url)
Reliability-related decisions reflect the expected useful life of the component, which is through the appropriate choice of a component alternative. The maintenance decisions are mainly concerned with the type of maintenance to be carried out during the warranty period. The warranty logistics decisions are related to deciding the service delivery network and management of spares. The details about the warranty related decisions at the design stage are discussed in the subsequent paragraphs.

As the failure frequency of a product is dependent on the reliability of the product, it will also significantly affect the warranty claims. With increase in product’s reliability, the number of warranty claims will decrease. Not having adequate reliability is costlier as failures result not only in higher warranty costs but also reduced sales and revenue due to the negative impact of customer satisfaction resulting from product failures. The data related to inherent reliability of components can be obtained from component manufacturers, from field failure records and from life tests conducted at the design and development stage.

The warranty claims data can be used for analysis of failures and subsequently making improvements into the design of the product. Warranty data are the primary mode of performance feedback regarding the ability of the product to perform its intended function in the hands of the customer. Warranty data are an accumulation of all incidents reported during the warranty period. The warranty period is that time and/or mileage during which the manufacturer will repair, with no charge or minimum charge to the customer, all incidents that occur during the system/vehicle warranty. The warranty claim data can be obtained from the dealers and service agents. Many web-based warranty management softwares are available in the market, which can help in effective processing of warranty data (SAS Institute Inc, 2008).

In a competitive environment, the total demand for first purchase sales depends on product attributes. These include the sales price and the warranty terms of the products. Manufacturer’s reputation depends on the reputation of its products and has a strong influence on the first purchase decisions of new customers. Product reputation has a similar effect on repeat purchase decisions. The sales data of the product compared with the competitor’s sales volume as well as share of the product in the market can be used to set the benchmarking and building the reputation in the market.

The type of maintenance will affect the number of failures and consequently the number warranty claims. For a given warranty period, the manufacturer can minimize the expected number of warranty claims through optimal maintenance decision making, which reduces the likelihood of failures. Optimal preventive actions need to be viewed from a life cycle perspective for the buyer and manufacturer.

Apart from the design-related issues, warranty logistics plays an important role in controlling the warranty cost. The manufacturer needs a dispersed network of service facilities that store spare parts and provide a base for field service. The service delivery network requires a diverse collection of human and capital resources and careful attention must be paid to both the design and the control of the service delivery system. The data related to the requirement of spare parts can be obtained from the sales department. Warranty logistics-related data can be acquired from the service agents and dealers, who provide service to the customers.

The feedback for a product can be obtained through customers in the form of feedback reports, consumer surveys and warranty claim data/failure data obtained from the dealers and service agents. Collected data provides ability to an organization
to track product failures and defects in order to recover warranted repair/part/labour costs from suppliers. Warranty claim data will be useful in early warning/detection of bad design, poor production processes, defective parts, poor materials, etc. Manufacturers analyze field reliability data to enhance the quality and reliability of their products and to improve customer satisfaction. A quick feedback mechanism needs to be developed in order to make the improvements as early as possible and reducing the number of defective units to be produced.

Warranty optimization using all the parameters and decision variables identified in the above framework is extremely complex. However, the optimization can be attempted by reducing the complexity to some extent. This can be done by considering a few significant decision variables out of the entire set.

In the next section a methodology for warranty optimization is presented with specific focus on component reliability, warranty policy type and duration.

4. Warranty optimization
In this section, a model for solving the warranty optimization problem is developed and demonstrated using a real life case of an automobile engine. We consider a case where the manufacturer of the engine wants to improve the reliability of the product by choosing appropriate component alternatives and also restrict the corresponding warranty cost to the certain proportion of the engine price by choosing appropriate warranty-related parameters. The decision variables considered are component alternatives, type of warranty policy and duration of warranty policy.

Currently the manufacturer offers a non-renewing free replacement warranty (FRW-NR) with a duration of one year. In the present paper, four types of warranty policies namely, FRW-NR, non-renewing pro-rata warranty (PRW-NR), renewing free replacement warranty (FRW-R), renewing pro-rata warranty (PRW-R) have been considered. The details of the methodology used are mentioned in following section.

4.1 Parameters estimation for failure distribution
As the two parameter Weibull distribution is most commonly used to model the failure behaviour of the mechanical components, the same is used in the present study to model the failure behaviour of components of the engine.

In the present study, the failure data were collected from the warranty database and the field failure records available at the service centers.

Components for which sufficient data were available, the standard distribution fitting method using the maximum likelihood Estimation procedure was used. However, there were cases where the field failure data was not sufficient. In such cases using only warranty data was not sufficient and an expert judgment-base approach was used for parameter estimation. This method was first proposed by Jager and Bertsche (2004) and a modified version was developed and used by Lad and Kulkarni (2010).

In both these studies, the method was proven to be sufficiently accurate and robust for parameter estimation. A brief account of the method is given below.

The idea behind the expert judgment-based parameter estimation is to determine the distribution parameters using the knowledge and experience of the experts. This is achieved by modeling the expert knowledge for a continuous random variable $t$, i.e., time to failure (lifetime) of any component for a given probability distribution. The use of expert knowledge to model a two parameter Weibull distribution is discussed in the following section.
The probability density function of the time to failure $t$ with Weibull distribution is given by:

$$f(t) = \left(\frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}\right) \cdot e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad \beta, \eta, t \geq 0 \tag{1}$$

In this method, the knowledge available with the expert regarding value of $t$ is captured and is converted into estimation of distribution parameters.

The data related to expert judgment for the components of the engine is collected from the experts from the engine manufacturing company, OEM and service centers who are directly involved with the post-sales support of the engine.

Experts are asked about the time period when the components mostly fail or most likely to fail. This value indicates the mode of the time to failure distribution and can be estimated with differentiating the Equation (1) with respect to $t$ and equating it to zero. Thus mode $X$ can be given by:

$$t_{mode} = X = \eta \cdot \left(\frac{\beta - 1}{\beta}\right)^{\frac{1}{\beta}} \tag{2}$$

Next, the experts are asked about the longest failure free life of the component they have observed. From the methodology proposed by Jager and Bertsche (2004), it is assumed that experts know about how many parts they have already replaced. So it can be assumed that sample size is known and it is represented by $N$. With this information the failure probability for the longest life time $Y$ can be determined using Equation (3) for the approximation of rank dependent failure probabilities (Ebeling, 2000):

$$F(t_z) \approx \frac{z - 0.3}{m + 0.4} \tag{3}$$

For the longest observed life ($Y$), $z = m = N$:

$$F(Y) \approx \frac{N - 0.3}{N + 0.4} \tag{4}$$

Thus the failure probability at the longest observed life ($Y$) for a Weibull distribution is given by:

$$F(Y) \approx 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{5}$$

Solving the Equations (2) and (5) simultaneously, the value of the Weibull distribution parameters is obtained. In the present study, the value of the $F(Y)$ is assumed as 0.990.

In the present paper only critical components are considered, the criticality depends upon the cost of the component and criticality and consequences of failure. So there are 29 components considered in the engine as critical components. The component alternatives along with their distribution parameters and cost are given in the Table I.

The component alternatives are selected based on the similar components used by the manufacturer in other types of engine models and variants but could be used directly or with a little modifications in the engine under study.

4.2 Warranty cost models
The warranty costs for different warranty policies considered in the present paper are calculated using Equations (6)-(9) as follows (Blischke and Murthy, 1994).
In the case of FRW-NR policy, the manufacturer agrees to repair or provide replacements for failed items free of charge up to a warranty duration $w$ from the time of the initial purchase. The cost function is given by Equation (6):

$$WC_{FRW-NR} = \begin{cases} C_c, & 0 \leq t_i \leq w \\ 0, & \text{otherwise} \end{cases} \sum_{i=1}^{m} t_i \leq w$$  \tag{6}

where, $C_c$ is the component cost and $w$ is the warranty duration $t_i$ is time to failure.

In case of PRW-NR policy, the manufacturer agrees to refund a fraction of the purchase price should the item fail before warranty duration $w$ from the time of the initial purchase. The cost function is given by the following equation:

$$WC_{PRW-NR} = \begin{cases} C_c \left(1 - \frac{t_i}{w}\right), & 0 \leq t_i \leq w \\ 0, & \text{otherwise} \end{cases} \sum_{i=1}^{m} t_i \leq w$$  \tag{7}

In the case of FRW-R policy, the manufacturer agrees to either repair a failed item or provide a replacement free of charge up to warranty duration $w$ from the initial purchase.

Table I. Component alternatives with cost and distribution parameters

<table>
<thead>
<tr>
<th>Sl. no.</th>
<th>Component</th>
<th>Alternative 1</th>
<th>Alternative 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost (Rs.)</td>
<td>$\eta$</td>
<td>$\beta$</td>
</tr>
<tr>
<td>1</td>
<td>Crank Case</td>
<td>2,559.82</td>
<td>13,496.37</td>
</tr>
<tr>
<td>2</td>
<td>Starter Motor</td>
<td>2,309.13</td>
<td>8,747.26</td>
</tr>
<tr>
<td>3</td>
<td>Fuel Pump Assly</td>
<td>1,835.32</td>
<td>8,199.72</td>
</tr>
<tr>
<td>4</td>
<td>Crank Shaft</td>
<td>1,488.09</td>
<td>9,932.81</td>
</tr>
<tr>
<td>5</td>
<td>Nozzle</td>
<td>1,350.53</td>
<td>9,364.98</td>
</tr>
<tr>
<td>6</td>
<td>Cyl. Head</td>
<td>1,184.33</td>
<td>9,331.37</td>
</tr>
<tr>
<td>7</td>
<td>FMA</td>
<td>1,100.00</td>
<td>13,496.37</td>
</tr>
<tr>
<td>8</td>
<td>BP Kit</td>
<td>1,089.61</td>
<td>8,333.48</td>
</tr>
<tr>
<td>9</td>
<td>Regulator</td>
<td>681.34</td>
<td>10,602.86</td>
</tr>
<tr>
<td>10</td>
<td>Ex. Muffler</td>
<td>672.42</td>
<td>8,199.72</td>
</tr>
<tr>
<td>11</td>
<td>Delivery Valve</td>
<td>587.38</td>
<td>4,373.63</td>
</tr>
<tr>
<td>12</td>
<td>CAM Shaft</td>
<td>495.84</td>
<td>28,851.96</td>
</tr>
<tr>
<td>13</td>
<td>Feed Pump</td>
<td>323.33</td>
<td>47,555.60</td>
</tr>
<tr>
<td>14</td>
<td>Crank Shaft Support</td>
<td>284.43</td>
<td>38,249.60</td>
</tr>
<tr>
<td>15</td>
<td>Connecting Rod Assly</td>
<td>267.88</td>
<td>4,665.68</td>
</tr>
<tr>
<td>16</td>
<td>Lub Oil Pump</td>
<td>258.09</td>
<td>18,083.35</td>
</tr>
<tr>
<td>17</td>
<td>CAM and Follower Set</td>
<td>242.68</td>
<td>29,065.05</td>
</tr>
<tr>
<td>18</td>
<td>Governor Gear</td>
<td>181.57</td>
<td>5,554.26</td>
</tr>
<tr>
<td>19</td>
<td>Governor Support Assly</td>
<td>201.26</td>
<td>5,301.43</td>
</tr>
<tr>
<td>20</td>
<td>Valve Set</td>
<td>154.01</td>
<td>10,146.41</td>
</tr>
<tr>
<td>21</td>
<td>Roller Tappet</td>
<td>126.44</td>
<td>5,301.43</td>
</tr>
<tr>
<td>22</td>
<td>Set of Rocker lever</td>
<td>122.13</td>
<td>6,420.42</td>
</tr>
<tr>
<td>23</td>
<td>Diaphragm</td>
<td>80.85</td>
<td>9,157.55</td>
</tr>
<tr>
<td>24</td>
<td>High Pressure Pipe</td>
<td>74.86</td>
<td>11,108.52</td>
</tr>
<tr>
<td>25</td>
<td>LE Bearing</td>
<td>48.24</td>
<td>12,767.51</td>
</tr>
<tr>
<td>26</td>
<td>Set of Bushes</td>
<td>61.60</td>
<td>49,520.84</td>
</tr>
<tr>
<td>27</td>
<td>Bush STD</td>
<td>49.44</td>
<td>49,520.84</td>
</tr>
<tr>
<td>28</td>
<td>Bush F.W.E. Side</td>
<td>45.07</td>
<td>49,520.84</td>
</tr>
<tr>
<td>29</td>
<td>Set of Valve Guides</td>
<td>37.15</td>
<td>14,013.14</td>
</tr>
</tbody>
</table>
purchase. Whenever there is a replacement, the failed item is replaced by a new one with a new warranty whose terms are identical to those of the original warranty. The cost function is given by the following equation:

\[
WC_{FRW-R} = \begin{cases} 
C_c, & 0 \leq t_i \leq w \\
0, & \text{otherwise}
\end{cases} \quad \text{till } t_i \leq w
\]  

(8)

In the case of PRW-R policy, the manufacturer agrees to provide, at a pro-rated cost, a replacement item for failed items up to a warranty duration \( w \) from the time of the initial purchase. The replacement item is covered under warranty identical to that of the original item purchased. The cost function is given by the following equation:

\[
WC_{PRW-R} = \begin{cases} 
C_c(1 - \frac{t_i}{w}), & 0 \leq t_i \leq w \\
0, & \text{otherwise}
\end{cases} \quad \text{till } t_i \leq w
\]  

(9)

In the present paper a simulation-based approach is used for calculation of warranty costs for different policies. All the components are assumed as a non-repairable. The process used for simulation is as given below:

1. First the number of simulations are set as \( n \).
2. For each simulation, the following process is repeated for \( m \) number of iterations. The number of iterations depend upon the fulfillment of the condition for given warranty policy:
   - Randomly generate values of reliability \( R(t) \) with uniform distribution between 0 and 1.
   - The value of \( t_i \), i.e. time to failure can be calculated by Equation (10) with a given value of \( \eta \) and \( \beta \). This is given by:
     \[
t_i = \frac{\eta \cdot [-\ln R(t_i)]^{\frac{1}{\beta}}}{b}
\]  
     (10)
   - Calculate the warranty cost using the cost functions for each of the warranty policy is given in Equation (6)-(9).
3. Calculate the cumulative warranty cost for each of the iteration till the condition for given warranty policy gets satisfied. This gives warranty cost per simulation.
4. Repeat the step number 2 and 3 for the \( n \) number of simulations.
5. The warranty cost for the \( n \) simulation is added up. This cost is then divided with number of simulations \( n \) to get the warranty cost per unit.

In the present case, the target is to restrict the warranty cost to around 2 percent of the price of the engine, which is 35,000. So the target cost for the warranty cost in this case is Rs. 700, which has been used as one of the goals for optimization.

Another requirement is that the MTBF obtained from the new solution should be higher than the existing one. The improvement in MTBF is achieved through selecting the proper alternatives available with the manufacturer. Higher reliability can be achieved by using the components with higher reliability, but this is achieved at a
higher cost. Choosing a proper alternative is a difficult task as trade-off needs to be achieved between cost and reliability. In the present case, the target for MTBF is set as 10 percent higher than the existing MTBF for five years of duration.

The MTBF for the engine under study is determined using the simulation-based approach explained earlier, except that simulation is run for five years of duration. The duration of five years is taken based on the typical duration before a major overhaul. The MTBF of an engine with $n$ components is determined using the Equation (11) and is given by (Ebeling, 2000):

$$MTBF = \frac{t}{\sum_{i=1}^{n} N_i(t)}$$

where, $t$ is time period over which MTBF is calculated.

$N_i(t)$ is the expected number of failures for $i$th component during time period $t$.

An assumption made here is that all the components of the engine are independent and failure of one component does not cause failure of other component. Using the above methodology the MTBF considering five years of duration for the current design was determined as 390 hr. As the target set for the MTBF is 10 percent higher than the current MTBF, the value to be achieved is 429 hr. This has been used as one of the goals for the optimization problem.

4.3 Objective function

The objective function is formulated using a deviation function for each of the target goals. The deviation function is calculated using a quadratic loss function (Taguchi et al., 1989; Ross, 2005). The warranty cost is represented by a smaller the better type of quadratic loss function, whereas the MTBF is represented by a larger the better type of quadratic loss function. Using above two deviation functions the objective function is formulated as a sum of the deviation functions and can be stated as follows.

Objective function:

$$\text{Minimize} \sum w_{MTBF} \cdot d^-_{MTBF} + w_{WC} \cdot d^+_{WC}$$

$$= 0.50 \times \frac{(1.10 \times MTBF_{\text{Current}})^2}{(MTBF_{\text{Target}})^2} + 0.50 \times \frac{(WC_{\text{Target}})^2}{(0.02 \times \text{Engine Price})^2}$$

where, $w_{MTBF}$ and $w_{WC}$ are weights for target goals; $d^-_{MTBF}$ and $d^+_{WC}$ are the negative and positive deviation functions for MTBF and warranty cost, respectively; $MTBF_{\text{Current}}$ and $MTBF_{\text{Target}}$ are current and target MTBF; $WC_{\text{Target}}$ is the target warranty cost.

In the present study, the manufacturer provided same preference to both the target goals so a weightage of 0.5 is given to each of the goals in Equation (12).

The optimization is carried out using a GA (Deb, 1999, 2001). The problem addressed in the paper is a mixed integer nonlinear programming (MINLP) problem and GA is a good choice for solving MINLP problems (Gantovnik et al., 2003; Ponsich et al., 2008).
Start

Select population size and no. of generations

Generate random population for component alternatives, warranty type and duration

Find out fitness function value for the population

Find out cumulative function values and normalized fitness function values for the population

Form a mating pool by selecting best chromosomes from population. It will be new population with good chromosomes may occur more than once

Select two parents from the mating pool and using crossover produce two new off-springs

Crossover finished?

Select single off-spring and using mutation operator produce new off-spring

Mutation finished?

Repair the chromosomes

Find out fitness values for the new population

Elite selection: select the best fitness value population among the previous population and replace it with worst of the current population

Find out maximum fitness function value from the population

Is best solutions achieved?

Yes

Finish

No

No

No

Yes

No

No
As the GA is naturally suitable for maximization problem (Mathew, 2012), the fitness function is converted to a maximization function and is given as:

\[
\text{Fitness function} = \frac{1}{\text{Objective function}}
\]  

(13)

### 4.4 Solution methodology and results

The GA parameters used to solve warranty optimization problem are: population size: 200, number of generations: 200, cross-over probability: 0.9 and mutation rate: 0.01.

The flowchart in Figure 2 shows the optimization process using GA. The results of the optimization are shown in Table II.

<table>
<thead>
<tr>
<th>Sl. no.</th>
<th>Component</th>
<th>Warranty duration (in months)</th>
<th>Component alternative</th>
<th>Warranty policy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Crank Case</td>
<td>23</td>
<td>2</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>2</td>
<td>Starter Motor</td>
<td>21</td>
<td>2</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>3</td>
<td>Fuel Pump Assly.</td>
<td>25</td>
<td>2</td>
<td>PRW-R</td>
</tr>
<tr>
<td>4</td>
<td>Crank Shaft</td>
<td>22</td>
<td>2</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>5</td>
<td>Nozzle</td>
<td>19</td>
<td>2</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>6</td>
<td>Cylinder Head</td>
<td>20</td>
<td>2</td>
<td>PRW-R</td>
</tr>
<tr>
<td>7</td>
<td>FMA</td>
<td>21</td>
<td>2</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>8</td>
<td>BP Kit</td>
<td>20</td>
<td>2</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>9</td>
<td>Regulator</td>
<td>17</td>
<td>2</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>10</td>
<td>Ex. Muffler</td>
<td>19</td>
<td>2</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>11</td>
<td>Delivery Valve</td>
<td>18</td>
<td>2</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>12</td>
<td>CAM Shaft</td>
<td>28</td>
<td>2</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>13</td>
<td>Feed Pump</td>
<td>17</td>
<td>2</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>14</td>
<td>Crank Shaft Support</td>
<td>17</td>
<td>2</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>15</td>
<td>Connecting Rod Assly.</td>
<td>20</td>
<td>2</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>16</td>
<td>Lub Oil Pump</td>
<td>16</td>
<td>1</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>17</td>
<td>CAM and Follower Set</td>
<td>18</td>
<td>1</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>18</td>
<td>Governor Gear</td>
<td>28</td>
<td>2</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>19</td>
<td>Governor Support Assly.</td>
<td>21</td>
<td>2</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>20</td>
<td>Valve Set</td>
<td>25</td>
<td>2</td>
<td>PRW-R</td>
</tr>
<tr>
<td>21</td>
<td>Roller Tappet</td>
<td>16</td>
<td>2</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>22</td>
<td>Set of Rocker lever</td>
<td>21</td>
<td>2</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>23</td>
<td>Diaphragm</td>
<td>27</td>
<td>2</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>24</td>
<td>High Pressure Pipe</td>
<td>18</td>
<td>1</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>25</td>
<td>LE Bearing</td>
<td>21</td>
<td>1</td>
<td>PRW-NR</td>
</tr>
<tr>
<td>26</td>
<td>Set of Bushes</td>
<td>16</td>
<td>1</td>
<td>PRW-R</td>
</tr>
<tr>
<td>27</td>
<td>Bush STD</td>
<td>26</td>
<td>1</td>
<td>FRW-R</td>
</tr>
<tr>
<td>28</td>
<td>Bush F.W.E. Side</td>
<td>20</td>
<td>1</td>
<td>PRW-R</td>
</tr>
<tr>
<td>29</td>
<td>Set of Valve Guides</td>
<td>21</td>
<td>2</td>
<td>PRW-NR</td>
</tr>
</tbody>
</table>

Table II. Results of optimization

### Table III.

<table>
<thead>
<tr>
<th>Warranty cost (Rs.)</th>
<th>MTBF (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal set</td>
<td>2 % of engine price</td>
</tr>
<tr>
<td>Target value</td>
<td>700</td>
</tr>
<tr>
<td>Achieved value</td>
<td>692</td>
</tr>
</tbody>
</table>

Comparison of achieved goal with target goals
Result obtained through optimization shown in Table II. It can be seen from the results that different component alternatives have got selected and each component is offered with a different warranty policy and duration. This could be justified based on the fact that customer wants the warranty period to be as long as possible. The manufacture on the other hand would want to offer a shorter warranty period to lower the warranty cost. The solution obtained is such that the warranty period offered is proportional to the expected life of a component. This will result into the customer perceiving a higher value in terms of warranty offered at the same time the warranty cost constraint set by the manufacturer are also met.

Based on the reliability of the components higher warranty period is offered for the components based on their reliability so that higher customer satisfaction can be achieved. The values of the goal achieved through optimization are shown in Table III.

It can be seen that warranty cost goal is achieved as per the target set by the manufacturer. The target set for the MTBF is also achieved and the value of the MTBF obtained is higher than the target value of the 429 hr., which will result into improved reliability of the engine. Figure 3 shows how the fitness value converges towards the solution. It can be seen that the solution gets stable after 130 generations. The time required for obtaining the solution was 20 hr.

As the distribution parameters were determined using expert judgment, there are chances of error in the values provided by the experts. To estimate the effect of error in

<table>
<thead>
<tr>
<th>Case no.</th>
<th>% of error in judgment</th>
<th>Warranty cost (Rs.)</th>
<th>MTBF (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>−10% in X and −10% in Y</td>
<td>855.35</td>
<td>427.16</td>
</tr>
<tr>
<td>2</td>
<td>−10% in X and +10% in Y</td>
<td>989.99</td>
<td>452.25</td>
</tr>
<tr>
<td>3</td>
<td>+10% in X and −10% in Y</td>
<td>620.34</td>
<td>426.10</td>
</tr>
<tr>
<td>4</td>
<td>+10% in X and +10% in Y</td>
<td>592.64</td>
<td>516.15</td>
</tr>
</tbody>
</table>

Table IV. Effect of error in expert judgment on distribution parameter estimation
the expert judgment, the solution achieved is tested for robustness using a combination of cases for a ±10 percent error in the values of mode (X) and maximum observed life (Y). The results for different combinations of error are shown in Table IV.

From the Table IV, it can be seen that case no. 1 gives higher values of warranty whereas the value of the MTBF is almost near set target. In case no. 2, the target value of the MTBF is achieved but the warranty cost is high. While in case no. 3, the warranty cost target is achieved whereas MTBF value is slightly less than the target value. In case no. 4, the target values are achieved for both warranty cost and MTBF. It can be seen that even though the goals are not achieved in all the cases, the deviation from the target values is small and the solution can be considered to be sufficiently robust.

5. Conclusion
In this paper, a conceptual framework is proposed that integrates the technology and commercial issues early at the design stage of a product to minimize the warranty costs in the most effective and efficient manner. Warranty costs can be reduced by taking warranty-related decisions at the design stage. The model for optimization of warranty is developed with a focus on reliability and warranty policies. The target goals set for the optimization are to restrict the warranty cost to a predetermined proportion of the engine price and to achieve a higher value of MTBF as compared to the current value. The model is illustrated using the case of an engine manufacture. The robustness of the result are evaluated through calculation of warranty cost and MTBF in the case of ±10 percent error in the expert judgment.

The conceptual framework proposed in this paper will further motivate researchers to work in this area. The model developed will help the designers to take appropriate decisions related to improvement in the reliability and selection of warranty parameters in order to minimize the warranty cost.

References


**Further reading**


**Corresponding author**

Prashant M. Ambad can be contacted at: pmambad@mech.iitd.ac.in

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