

Optimal Preventive Maintenance Schedule Based on Lifecycle Cost and Time-Dependent Reliability

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ABSTRACT

Reliability is an important engineering requirement for consistently delivering acceptable product performance through time. It also affects the scheduling for preventive maintenance. Reliability usually degrades with time increasing therefore, the lifecycle cost due to more frequent failures which result in increased warranty costs, costly repairs and loss of market share. In a lifecycle cost based design, we must account for product quality and preventive maintenance using time-dependent reliability. Quality is a measure of our confidence that the product conforms to specifications as it leaves the factory. For a repairable system, preventive maintenance is scheduled to avoid failures, unnecessary production loss and safety violations. This article proposes a methodology to obtain the optimal scheduling for preventive maintenance using time-dependent reliability principles. An optimization algorithm maximizes the time for preventive maintenance by improving the system reliability, so that the lifecycle cost stays below a specified target. The lifecycle cost includes a production, an inspection, and an expected variable cost. All costs depend on quality and/or reliability. Preventive maintenance is performed at the time when the improved reliability falls below an acceptable reliability target. The methodology also identifies the most critical component(s), or failure modes, which if repaired, will improve the system reliability the most. We demonstrate the proposed approach using an automotive roller clutch example.

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1. INTRODUCTION

Customers and product manufacturers demand continued functionality of complex equipment and processes. Degradation of material properties in time and stochastic operating conditions such as loading, result in a lowered resale value due to inconsistent performance and even premature failure, increased warranty cost and customer annoyance. In product design, it is desirable to consider the attributes of survivability, quality, reliability, maintainability, and safety, and reduce scrap, rework, and maintenance time. This can be achieved by selecting dimensions and materials so that the system performance satisfies all design specifications over the planned life-time. An important factor in a customer's buying decision is the total lifecycle cost which can be affected considerably by a high maintenance cost.

Quality and reliability are two important attributes that must be addressed simultaneously. Quality measures the conformance to design specifications as the product leaves

the factory to begin its lifecycle. In this work, quality is quantified by the probability that the performance measures meet the specifications at the initial time of its lifecycle; i.e. right after it is produced. Reliability is defined as the probability that the system will perform its intended function for a specified interval of time, under stated operating and environmental conditions. Reliability is, therefore, related to product functionality which is determined by the so-called "hard" and "soft" failures [1, 2]. In a hard failure the system loses functionality due to a complete breakdown, while in a soft failure the system is functional but one or more performance measures are out of conformance.

Maintenance is also an important attribute. It involves any activity that can restore or recover a system should it breaks down or gets out of order. This type of maintenance, known as repair or unscheduled maintenance, can be very costly and should be avoided. In contrast, a scheduled maintenance occurs before any failure or malfunction in order to keep the system in working order preventing a potentially serious

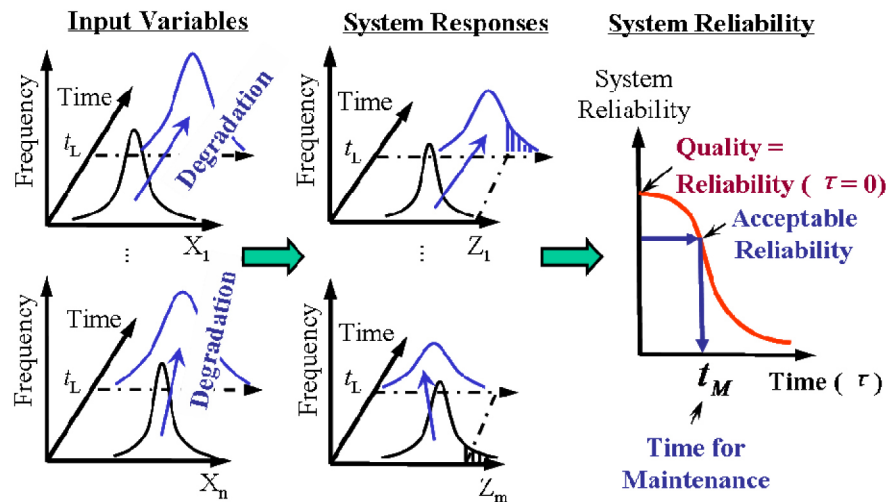


Figure 1. Uncertainty propagation for time-dependent system reliability (modified from Savage et al [1])

damage. Preventive maintenance is therefore, a schedule of planned maintenance actions performed in an attempt to avoid failures, unnecessary production loss and safety violations.

In preventive maintenance, when the maintenance frequency increases, the deterioration failure rate is reduced [3]. As a system cannot be maintained at all times, a way is needed to decide when inspection/maintenance is needed. To avoid unnecessary maintenance, which increases the cost and may also increase the risk of further wear, the effectiveness of a preventive maintenance schedule should depend on quality, reliability and a lifecycle cost analysis. Barlow and Hunter [4] did a pioneering work on optimum preventive maintenance policies. Since then, many works have been done along this line. Survey papers such as in [3,4,5,6,7,8] cover the subject of optimal maintenance.

In our previous work [9], a design methodology was presented based on the product lifecycle cost considering uncertainty and variability through time-dependent reliability in order to simultaneously meet the needs of the manufacturer (low production, inspection and warranty costs) and the customer (customer satisfaction and better resale value). Although design under uncertainty, or reliability-based design (RBD), has been extensively studied [10,11,12,13,14], RBD considering the lifecycle cost has not attracted much attention due to the complexity and high computational effort in calculating the time-dependent reliability. Only a limited number of studies exist which mainly use simplifying assumptions in the calculation of time-dependent reliability [1, 2, 15,16,17] or use lifecycle cost in design to account for reliability, maintenance and warranty [18,19,20].

The intent of this paper is to increase the time before preventive maintenance is needed using design optimization, considering time-dependent phenomena such as degradation of certain components. Consider a system with multiple responses which must conform to certain specification limits set by the designer. For demonstration purposes, degradation

in time changes the statistics of the inputs (e.g. operating loads, material properties, etc.) and the resulting statistics of the responses. Fig. 1 shows a probabilistic view of this process over time.

At the left of Fig. 1, the probability density functions of the input random variables X_i change over time due to degradation. They are therefore, denoted by $X_i(\tau)$ to indicate that they are time-dependent. The designer may control only the initial probability density functions. The system response distributions also change over time due to the changes in the inputs. It is assumed that each response $Z_j(\tau)$ is a function of the inputs $X_1(\tau), X_2(\tau), \dots, X_n(\tau)$. The system reliability versus time is shown at the right of Fig. 1. It is built over time by calculating the system time-dependent reliability or probability of conformance. As a special case, quality can be viewed as the initial reliability at $\tau = 0$. If an acceptable reliability level is prescribed, the time to maintenance t_M can be determined. The efficient estimation of the time dependent reliability is thus the key to determining the time to maintenance. Maximizing the time to maintenance for a given level of system reliability is the goal of this research.

To date, few researchers have proposed methods to estimate the system reliability by discretizing time and using time invariant limit-state methods. Using a different approach, Son and Savage [21] tracked time-variant, limit-state surfaces in the standard normal space. Incremental failure probabilities were evaluated and summed at discrete time intervals to estimate the mean time to soft failure (MTTSF) and its variance. It is easier, however, for managers and engineers to understand monetary measures rather than the traditional reliability measures. Thus, monetary measures are commonly used as optimization objectives or constraints. The costs of degrading systems can be used to determine the means and tolerances.

With respect to performance reliability, there have been a few research activities in which the present value (or worth)

of expected quality losses are used. The latter are measures of nonconformance of the responses with respect to desired specifications. Chou et al. [22, 23] augmented present value with the production cost C_P to form a total cost, and then performed tolerance allocation by formulating an optimization problem. Son et al. [24] used a probabilistic expected loss of quality and extended its application to degrading mechanistic systems with multiple target/smaller/larger-is-best performance metrics. The probabilistic measure was optimized using aspects of Reliability-Based Design Optimization (RBDO) methods.

In our previous research [9], we used a time-variant reliability analysis and loss of quality costs [2] in the design of multi-response systems. The optimal design was calculated by minimizing the lifecycle cost while satisfying quality and reliability constraints throughout the lifecycle of the system. The conformance of multiple responses was treated in a series-system fashion. In this research, we maximize the *first* time for preventive maintenance subject to an acceptable quality, time-dependent reliability and cost constraints. An automotive roller clutch example illustrates our approach and provides details on the usefulness and practicality of the proposed methodology for optimal preventive maintenance scheduling.

The paper is organized as follows. After a brief introduction to time-dependent reliability analysis in Section 2, the definition of lifecycle cost and its calculation are provided in Section 3. Section 4 presents the optimization problem for maximizing the time to maintenance and Section 5 uses an automotive roller clutch example to demonstrate the benefits of the proposed methodology. Finally, a summary and conclusions are provided in Section 6.

2. RELIABILITY ANALYSIS

In reliability analysis, we estimate the probability of failure due to variability and/or uncertainty using a probabilistic quantification of the variation/uncertainty and a definition of failure. In time-independent (or time-invariant) reliability analysis, the uncertainty is quantified using random variables. A time-independent limit state function $g(\mathbf{X})$ is used, where the vector $\mathbf{X}$ represents the input random variables with a joint probability density function $f_{\mathbf{X}}(\mathbf{x})$. The probability of failure is given by

$$P_f = P(g(\mathbf{X}) < 0) = \int \cdots \int_{g(\mathbf{x}) < 0} f_{\mathbf{X}}(\mathbf{x}) d\mathbf{x}. \quad (1)$$

Because the multi-dimensional integral of Eq. (1) is difficult to evaluate, various analytical and simulation-based methods have been developed [10,11,12,13,14, 25,26,27,28,29,30].

2.1. TIME-DEPENDENT RELIABILITY ESTIMATION

In many engineering systems, the system response (output) depends on time and is described by a random process $g(\mathbf{d}, \mathbf{X}, \tau)$. For each realization of the input deterministic variables $\mathbf{d}$ and random variables $\mathbf{X}$, the output is a time-dependent sample function. Denoting the time interval of interest by $[t_{\min}, t_{\max}]$, the probability of failure within this time interval is defined as

$$P_f^c(\mathbf{d}, \mathbf{X}; t_{\min}, t_{\max}) = P(\exists t \in [t_{\min}, t_{\max}], g(\mathbf{d}, \mathbf{X}, t) < 0), \quad (2a)$$

or

$$F^c(\mathbf{d}, \mathbf{X}, t) = P_f^c(\mathbf{d}, \mathbf{X}; 0, t) = P(\exists \tau \in [0, t], g(\mathbf{d}, \mathbf{X}, \tau) < 0) \quad (2b)$$

where F^c denotes what is known as *cumulative* probability of failure [30], indicating that failure occurs if the limit state function becomes negative at least at one instance within the time interval. In general, the definition of the *cumulative* probability of failure in Eq. (2) is different from the *instantaneous* probability of failure

$$P_f^i(\mathbf{d}, \mathbf{X}, t) = P(g(\mathbf{d}, \mathbf{X}, t) < 0), \quad (3)$$

which is calculated in a quasi-steady sense by fixing time t and replacing the random process by a random variable. As a result, it does not account for possible failures before time t . The conceptual difference between the cumulative and the instantaneous probabilities of failure is very important.

In our previous work [9], we gave a brief literature review of time-dependent reliability evaluation methods, and presented a composite limit state concept to ease the estimation of the time-dependent reliability in Eq. (2). The composite limit state in the time period $[0, t]$ is defined as

$$g^c(\mathbf{d}, \mathbf{X}, t) = \{\exists \tau \in [0, t], g(\mathbf{d}, \mathbf{X}, \tau) < 0\} \dots \approx \bigcup_{l=0}^L \{g(\mathbf{d}, \mathbf{X}, \tau_l) \leq 0\}, \quad (4)$$

where $\tau_l \in [0, t]$ for $\tau_0 = 0 < \tau_1 < \dots < \tau_l < \dots < \tau_L = t$. If $L \rightarrow \infty$, the approximation in Eq. (4) becomes an equality.

The event of first passage in a given time interval is equivalent to the event of the maximum response in the same time interval exceeding an allowable threshold value. The definition of the cumulative probability of failure $F^c(t)$ is thus equivalent to the probability of first passage. If the maximum response in the time period $[0, t]$ is