# On optimal maintenance strategy using discrete-event Monte Carlo simulation

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## Abstract

*Asset maintenance plays crucial role in efficiency and economy of manufacturing. In this contribution a brief taxonomy of asset maintenance strategies is first presented. The key of the approach suggested below is in modeling the degradation processes as a hidden Markov process. Based on that the maintenance strategies can be formulated as a stochastic optimisation problem where different criteria like cost and risk, for example, can be utilized. A Monte Carlo simulation example is provided in order to illustrate the idea.*

## 1 Introduction

In a continuously growing global market, productivity plays a key role in keeping the manufacturing companies stay competitive. High productivity can be achieved through certain availability and reliability level. These can be increased through adopting efficient maintenance practices, by focusing on different types of maintenance strategies accompanied by adequate technologies [1].

Unlike capital investments in new production equipment, the benefit of adopting maintenance strategies based on novel technologies for condition based maintenance, within an asset maintenance management framework is not easily assessed for its financial impact. As expected, the prospective customers of CBM technologies want to know how the implementation of this technology will benefit their organization. The most common response from individuals in the field is that CBM decreases maintenance costs, increases operational availability and improves product quality. In order to understand the practical benefit of the implementation of CBM, a customer need financial assessment to justify such an investment [2].

The purpose of the paper is through development of a conceptual model and performing computer simulation, to evaluate the suitability of different maintenance strategies, from a cost point of view. By assuming that maintenance is a stochastic process, the cost function related to a particular maintenance strategy is a random variable whose probability density function (pdf) is calculated via Monte Carlo simulation. Given a set of pdf's corresponding to a set of candidate strategies it is possible to design a ranking procedure to discriminate between different strategies.

## 2 Asset maintenance concept

Maintenance is a process where a combination of technical, administrative and managerial actions are performed during the life cycle of an asset, in order to keep or restore it to a state in which it can perform the required function [3]. This implies that maintenance should be considered as actions taken to prevent or to repair an asset, or its component from failing. Here, in the context of this paper "asset" is considered as: any physical component in possession of an organization, which enables services to be provided, in order to produce positive economic value.

### 2.1 Maintenance strategies

According to the definition stated before, we can extract two kinds of actions that occur during the maintenance process. The first types are actions oriented towards retaining appropriate health conditions of an asset. Second ones are actions dedicated to restoring the item into the state in which it can perform its required function. Based on this we can distinguish two kinds of maintenance strategies, *reactive* and *proactive*.

The *reactive* or unplanned maintenance strategy covers the entire activities associated with repairing or replacing asset components after their failure. This strategy can be further divided into emergency and corrective maintenance (CM) strategy as shown in Figure 1. Emergency or the so called crisis-oriented maintenance demands immediate attention by the maintenance engineers and it is carried out as fast as possible in order to bring a failed asset to a safe and operationally efficient condition.

*Corrective* maintenance (CM) is a strategy where actions are performed after a fault appearance and its goal is to restore the asset into initial operability.

The reactive maintenance strategies are contrasted with the proactive approach, which aim is to avoid asset failures. The proactive approach responds on a basis of asset assessment and preventive or predictive procedures as a strategy for stabilizing the reliability and availability of assets. The main idea is to direct maintenance actions to failure root causes, not active failure symptoms. Several types of strategies comprise the proactive i.e. planned approach: preventive, predictive and improvement.

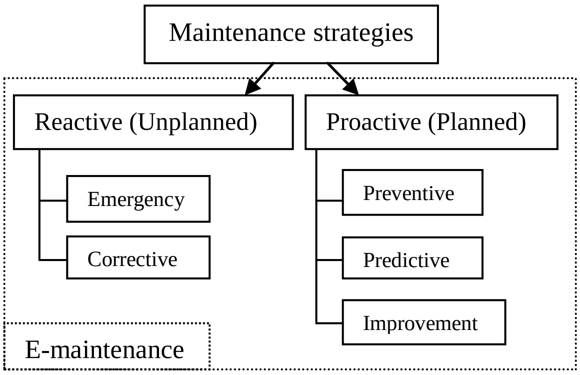



Figure 1. Taxonomy of maintenance strategies

The preventive maintenance strategy includes activities that are performed on time schedule in order to prevent any unwanted failures. Furthermore, its goal is to reduce or mitigate asset degradation, with the aim of sustaining or extending its productive life [4]. Usually preventive actions are carried out at predefined intervals or according to some recommended criteria.

The aim of the improvement maintenance strategy is to reduce or eliminate recurring and frequent failures. It covers a set of activities intended towards simplifying maintenance tasks. Its intention is to raise the plant performance, from a maintenance point of view by redesigning and modification of assets that are prone to frequent failures.

Predictive maintenance is defined as activities and measurements that detect the onset of system degradation, allowing random unwanted failures to be eliminated prior to any significant deterioration happens [4]. This strategy differs from the preventive strategy by basing maintenance actions on actual condition of the asset, rather than on some preset schedule. The predictive maintenance strategy is based on various techniques and tools for continuous (online) asset condition based monitoring. Condition based maintenance is a form of predictive maintenance which consists of a set of actions, based on real-time or near real-time assessment of asset condition. Information is obtained from embedded sensors and/or external tests and measurements are conducted by portable equipment. The trigger for maintenance activity is a measured parameter that gives early warning and indication of the current asset condition. A component or an asset is repaired or replaced as soon as the monitoring value of the measured parameter exceeds the normal.

The growth of information and communication technologies (ICTs) resulted in foundation of new advanced level of maintenance approach called e-maintenance. The idea of e-maintenance is that via monitoring plant asset i.e. collecting information about its condition, to link the production and maintenance operation system. E-maintenance arises as a step forward towards improved integration of asset maintenance management. It cannot be classified as a single technology or a maintenance strategy. It should be considered as an effective toolset that assists the progress of implementation of the enterprise maintenance strategy.

## 2.2 Maintenance activities

All previously mentioned maintenance strategies consist of a set of maintenance activities. Most common activities performed [5] are: monitoring, inspection, routine maintenance, repair, and overhaul.

- *Monitoring* is an action performed either manually or automatically. It is intended to observe the actual state of the asset.
- *Inspection* is a routine which is conducted in order to determine the state of an asset. The aim is to make regular maintenance inspections so deterioration process and failures can be identified.
- *Routine maintenance* includes regular or repeated maintenance activities intended for a regular upkeep of an asset. This type of maintenance activity is comprised form activities such as: cleaning, tightening of connections, adjustments and tuning, oil and filter changing, lubrication...
- *Repair* is comprised of all physical actions aimed to restore the required function of an asset. It consists of fault diagnosis, correction, and function check-out.
- *Overhaul* is an extensive set of actions which usually involve partial or complete disassembly of an asset in order to replace or to repair every defective or worn component.

## 2.3 Maintenance costs

The total cost of maintenance $C_m$ is comprised of several components: cost of inspection ($C_i$), cost of failures ($C_f$), cost of storage ($C_s$).

$$C_m = C_i + C_f + C_s \qquad (1)$$

The inspection costs cover the expenses related to the periodic maintenance inspection tasks. The assumption is that the state of the system is not known unless it is inspected. Namely, in such a case we have sequential inspections, which are performed at some interval $t$, and the cost for each inspection is fixed at $C_i$. Inspection costs include all expenses for direct outsourced labor (maintenance personnel), spare parts used specifically for an inspection, and expendable material required. In case that after the inspection the system is found to be in a certain deterioration state, adequate maintenance action is performed. This implies that either a component is repaired or replaced with a cost of failure $C_f$. Depending on the type of the maintenance action performed, failure cost can be further divided to cost for minor or major maintenance action. Then either a component is repaired or replaced with a cost $C_{cr}$, or a whole system is repaired or replaced with a cost $C_{sr}$. In a case if unwanted failure occurs, corrective maintenance action is performed with a cost $C_r$.

In order to maintain an asset it is necessary to have an inventory of essential spare parts for its entire life cycle. The spare parts by their nature are only placed in service when an asset failure occurs and the bad part is swapped out with a spare one form the inventory. The cost of storage $C_s$ covers the cost needed for financing and handling the necessary spare parts and similar expendable materials.

## 3 Asset health and the process of deterioration

All assets are subjected to ageing and wear through the course of their lifetime. In general, deterioration process is accompanied with failures. Modeling the process of deterioration and failure occurrence is important because it will help to determine the best maintenance strategy for an asset. The idea for modeling these processes is based on the concept of the asset life curve. There are three major factors that are responsible to the deterioration behavior of an asset: physical characteristics, operating practices, and maintenance strategy. Different maintenance strategies may result in slowing down the deterioration process and thereby extend the asset life time [6].

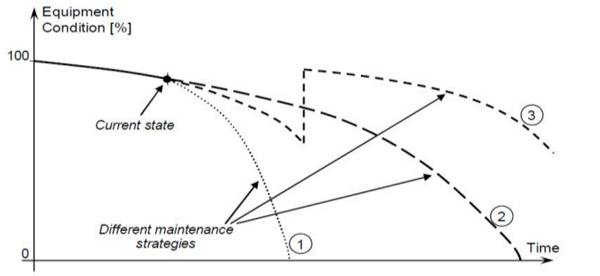



Figure 2. Life curves of an asset under different maintenance strategies (presented in [6])

## 4 Modeling deterioration and maintenance processes

Deterioration is clearly a continuous process; however we can model and observe the process as a discrete sequence of events in time. The assumption is that four deterioration states, that reflect the system condition, can be identified with reasonable accuracy: normal ($S_1$), minor deterioration ($S_2$), major (significant) deterioration state ($S_3$), and failure state ($F_1$) as shown in Figure 3.

States $S_1$, $S_2$, and $S_3$ are considered as consecutive deterioration but workable states while $F_1$ represents the state when the system is entirely unavailable.

In order to slow down the deterioration process, maintenance actions are performed. Therefore, inspections on the asset are performed in order to determine its condition. According to the inspection, decision is made whether and which type of maintenance actions should be performed. Based on this assumptions inspection ($I_i$) states, minor ($MM_i$) and major ($M_i$) maintenance states are added in to the model. The motivation of adding different types of maintenance is to recognize their differences in condition improvement and economic cost.

In the model, a possibility of transition between states is added. Thus, to formulate the model we make the following assumptions:

1. The duration of each stage of deterioration as well as times for repairing a failed asset is exponentially distributed.
2. The transition rates between deterioration states are $\lambda_{12}$, $\lambda_{23}$, and $\lambda_{3f}$ subsequently.
3. The inspection rate is denoted $\lambda_I$.
4. $\lambda_{MMi}$, $\lambda_{Mi,}$, and $\lambda_{Mc}$ are the rates corresponding minor, major or corrective maintenance actions after which the system enters deterioration state $S_i$.
5. The transition rates form deterioration failure state is $\mu_1$.

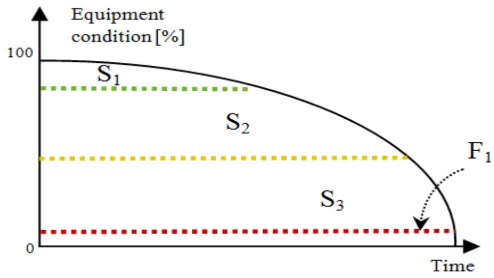



Figure 3. States that reflect the system condition

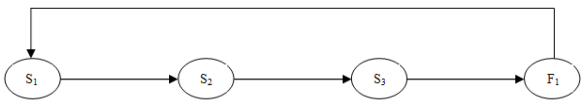



Figure 4. Model of the process of deterioration

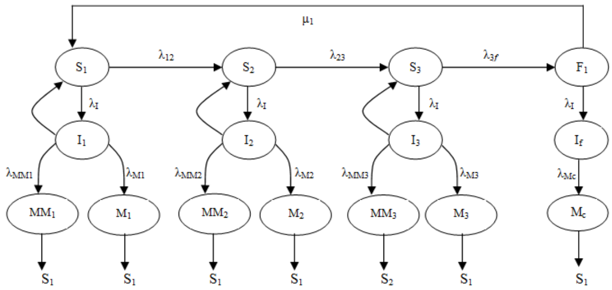



Figure 5. Deterioration and maintenance processes model

*Comment.* The transition rates are key to the model and generally it is not trivial to identify their values. There are three possible sources to obtain the estimates:

(i) Data driven approach based on estimation of the parameters of the probabilistic model, which is carried out from data gathered during past inspections.

(ii) From reliability data issued by the manufacturers of the components.

(iii) From extensive stochastic simulation of damage propagation via detailed first principle model.

## 5 Ranking the maintenance strategies

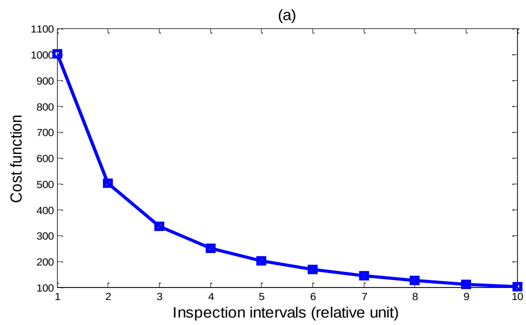
Any maintenance strategy above is characterized by a consistent set of inspections and repair actions, which are parameterized by a set of $k$ parameters $u \in R^k$, which can be e.g. inspection intervals in periodic maintenance. The most often performance indicators, used to carry out ranking are economic cost (1) and reliability. Generally we have the problem of multi-objective optimization. For the sake of simplicity let us focus on one objective only, i.e. cost. Since the degradation process is stochastic, the cost $C_m$ resulting from maintenance strategy over an assessment horizon $T$ is stochastic as well. Its probability density function $p(C_m)$ depends on $u$ and cost parameters. With pdf in hand one can define various selection criteria, so that search for optimal $u^*$ can be done for example in the following manner:

$$u^* = arg_u \min p(C_m (u)) \leq P_0 \qquad (2)$$

where $P_o$ means the allowed tolerated probability for excessive costs. The constraint accompanying criterion function (2) is degradation model, which defines transition from one condition state to another.
Analytical calculation of (2) is notoriously difficult, better said, it is practically impossible to be performed in closed form. Therefore a feasible solution is Monte Carlo simulation. The idea is to perform a suitable large set of simulation runs over the horizon $T$ with prescribed transition rates and in the degradation model and then at the end of run calculate the implicating cost. Hence with many repetitions we get the histogram (pdf) of the cost and then search for optimum (2) via nonlinear optimization methods.

## 6 Simulation results

In order to illustrate the approach we take a Markov model similar to that in Figure 5. The transition process from one condition state to another is defined by exponential distribution. The mean transition times are taken $T_{S1 \to S2} = 4$, $T_{S2 \to S3} = 2$, $T_{S3 \to F1} = 1$. The horizon $T=1000$ of units of time and the number of Monte Carlo runs is 200. The probability rate for worst costs is $Po=0.1$.
Two cases focusing on search for optimal inspection intervals in periodic maintenance are presented to emphasis the role of costs of action. First, the inspection costs in all the states are equal. Intuitively, it makes sense to have large inspection intervals. In the second case states 1-3 is assumed to be 1 (relative) unit, while the cost of repair is very high 100. Naturally, in that case it makes sense to choose relatively frequent inspections (Fig.6b) in order to avoid failure.
In Figure 7 two criteria are depicted. Obviously, for the final assessment of the strategies only economy is not enough, but a compromise between the two criteria should be taken into account.



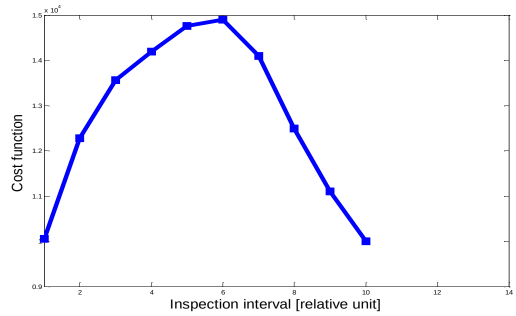




Figure 6. Cost function due to different costs of inspection (a) $C_{S1}$= =$C_{S2}$= $C_{S3}$= $C_{F1}$=1, (b) $C_{S1}$= $C_{S2}$= $C_{S3}$=1, $C_{F1}$=100.

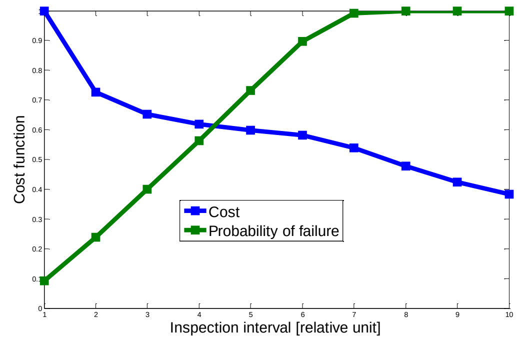



Figure 7. Dependence of two performance indicators (cost of inspection and failure risk) as function of inspection intervals.
$C_{S1}$= 1,$C_{S2}$=2, $C_{S3}$=3, $C_{F1}$=10.

## 7 Discussion

In this paper, an approach for defining the optimal maintenance strategy using discrete-event simulation is presented. Since the closed form solution is impossible to find, we propose a method where Monte Carlo simulation is used to obtain the optimal inspection interval. By using this approach asset maintenance scheduling can be improved, which will result in avoiding unexpected failures and consequently decrease maintenance costs.
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