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# Age-related maintenance versus reliability centred maintenance: a case study on aero-engines

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## Abstract

Reliability Centred Maintenance (RCM) is a procedure carried out as part of the logistic support analysis (LSA) process and is described in the US Department of Defence Military Standards (Mil Std 2173). RCM allows logisticians the opportunity to determine the best maintenance policy for each component within a system. However, the only data that are available to carryout RCM using Mil Std 2173 are of MTBF. This implies that all the necessary mathematical models need to be based on the exponential distribution. This is a serious drawback to the whole concept of RCM as the exponential distribution cannot be used to model items that fail due to wear, or any other mode that is related to their age. In this paper, a new approach to RCM is proposed using the concepts of *soft life* and *hard life* to optimise the total maintenance cost. For simplicity, only one mode of failure is considered for each component. However, the model can be readily applied to multiple failure modes. The proposed model is applied to find the optimal maintenance policies in the case of military aero-engines using Monte Carlo simulation. The case study shows a potential benefit from setting soft lives on relatively cheap components that can cause expensive, unplanned engine rejections. © 2000 Elsevier Science Ltd. All rights reserved.

*Keywords*: Hard life; MTBF; Maintenance-free operating period; Opportunistic maintenance; Reliability centred maintenance; Simulation; Soft life

## 1. Introduction

Reliability Centred Maintenance [1,2] (RCM) is designed to minimise maintenance costs by balancing the higher cost of corrective maintenance against the cost of preventive maintenance, taking into account the loss of potential life. For mechanical components, one cause of failure is cracking, which if left untreated could result in one or more pieces of metal becoming detached. The forces involved in an aero-engine are such that if this happens then it can cause serious damage to the engine and sometimes to the aircraft. For non-safety-critical components (those items whose failures are extremely unlikely to result in the loss of the aircraft and/or human life) failure can still be very expensive. It may result in an engine failure or damage to other components. Either way, it will almost certainly require an engine removal.

The ideal maintenance plan would be to replace the component just before it is about to fail. This can only be done if there is a high probability of being able to detect that the component has started to fail. For a mechanical component, this requires that there is a high probability that it will be inspected between the time when a crack first becomes visible and when the component breaks and, that the inspection process will actually identify a crack if one is present. Under ideal conditions, i.e. bright new metal with no oil or dirt contamination, a crack first becomes visible, to the naked eye, when it is 0.1 mm long. Normally, unless the engine is stripped down to part level, inspection has to be done using an *intrascope* or *boroscope*, which can often only see a part of the surface and then may be at a very oblique angle. The surface being inspected is usually contaminated and the picture seen through one of these instruments is difficult to interpret. The conditions under which the inspector has to work may be anything but ideal: cold, wet, dark, windy, contorted or even blinded by sunlight.

RCM is defined as part of the logistic support analysis (LSA) exercise and, by implication, should use the data held within the LSA record (LSAR) database. This database holds just one piece of information relating to the time to failure for each failure mode of each component. This item of data is the “MTBF”—mean [operating] time between failures. The only (continuous) failure distribution that can

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be defined by a single parameter is the exponential distribution. The unique property of the exponential distribution is that replacing an old, but still functional component with a new one does not improve, in any way, the probability that it will survive the next hour, day or year. To attempt to overcome this, it has been recognised (by the Department of Defence) that many components crack and that, if the crack propagation time is reasonably long, and the components are inspected sufficiently frequently, there is a high probability of detecting a crack before the component actually fails. In practice, very little is usually known about crack propagation times, either with respect to their duration or the variance, so it is almost impossible to determine the probability of detecting a crack given a routine inspection probability. The effectiveness of inspection—the probability of detecting a crack, given one is present, is usually unknown.

The second deficiency is that the exercise is supposed to be done on each component in total isolation. It is assumed that when the system fails it is the result of one, and only one, component failing and when it is recovered only that component which failed is repaired or replaced. Whilst this may be true for some systems (or subsystems) such as electronic equipment, it is rarely the case for mechanical ones. Typically, for military gas turbine engines, over 50% of the modules, which comprise the engine, will be replaced (known as *opportunistic maintenance* or *on-condition maintenance*). The failure of one component can often cause significant damage to several other components within the engine. When an engine is disassembled, it becomes possible to inspect many of the components, which are otherwise inaccessible. These may be damaged, worn or corroded, and so will need to be repaired or replaced. Because it is expensive to remove and strip an engine, the opportunity will also be taken to replace safety-critical components, which are nearing their hard life. With aero-engines, it is quite possible for failed components to go undetected for some time, often until the engine is removed. Such failures may cause small increases in vibration, reduction in thrust or specific fuel consumption. These factors may lead to the engine being run hotter (at higher throttle settings) to achieve the required performance and hence could lead to more rapid wear/deterioration of some other components. This effect is difficult to quantify and has not been considered in this paper.

The Department of Defence has, however recognised that when engines and/or modules are reconditioned (usually at Depot level or by the contractor), unnecessary work may be done and, parts may be replaced prematurely. The RCM process attempts to reduce this by requiring that parts which are unlikely to have failed (based, of course, on MTBF!) should not be inspected for anything other than obvious damage. In particular, parts that have a protective coating should not be stripped (of that coating) unless there is evidence to suggest that the coating has been damaged or compromised. This is based on the engineering maxim “unless it’s broken don’t fix it”.

In this paper we propose an alternative method to RCM using the concepts of *hard life* and *soft life*. The proposed new methodology is applied to find the optimal maintenance policy for aero-engines. Monte Carlo simulation is used to solve the mathematical model developed in the paper.

## 2. Alternative approach to reliability centred maintenance

At this point, it is convenient to introduce the concepts of *hard life* and *soft life* [3]. *Hard life* is defined as the age of the component, at or by which the component has to be replaced. Upon achieving this age, the system or subsystem containing the given component will be rejected for subsequent recovery (by part exchange). It is, therefore, *age based preventive replacement*. This concept is already in common use with safety-critical parts such as discs, which can cause loss of the aircraft if they burst. Associated with a hard life is usually a minimum issue life (MISL) which specifies how many flying hours the (safety-critical) part must have remaining for it to be re-issued—i.e. re-fitted into an engine. The purpose of the MISL is to reduce the number of unnecessary engine removals and recoveries that are expensive and, as such, is a purely economical device.

*Soft life* is the age of the component after which it will be rejected the next time the engine or one of its modules, containing it, is recovered (*age based opportunistic replacement)*. It is effectively the same as the MISL except that it can apply to any part (not just those with a hard life) and it is the age (from new), not the hours remaining to the hard life. Thus the fact that a component has exceeded its soft life would not be sufficient reason to ground the aircraft in order to remove the engine whereas this would be cause for rejection if it had exceeded its hard life.

The cost of a planned arising, one done to replace a component which has achieved its hard life, is likely to be considerably less than that of an unplanned arising. Firstly, it can be scheduled at the operator’s convenience, so minimising disruption to operation. Secondly, because the component has not actually failed, there will be no *caused* or *secondary damage*. Offset against this, however, is the fact that the component will have been replaced prematurely, i.e. it is likely to have lasted for a number of hours more before it actually failed. This means that, over the life of a fleet of aircraft, there could be more engine removals and recoveries than would otherwise have been the case. Given that the cost of a planned arising is less than that of an unplanned one and, that the probability of an unplanned arising can be reduced by replacing a given component before it fails, there may be an optimum age at which the given component should be replaced. If the cost of a component is relatively small, compared to the cost of a Line Replaceable Item (LRI) removal, there is likely to be an optimum value for the soft life. Note that the longer the LRI lasts, between removals, the more likely the soft-lifed