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

J. Crocker a, U.D. Kumar b, *

a MIRCE Akademy, PO Box 198, Exeter, Devon EX2 7YX, UK
b Centre for Management of Industrial Reliability, Cost and Effectiveness, University of Exeter, Exeter EX4 4QF, UK

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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.

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
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 recognized (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 distribution or the variance, so it is almost impossible to determine the probability of detecting a crack given a routine inspection at a 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 components which are unlikely to have failed (based, of course, on past experience) 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 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-lived
part will fail before the soft-life policy has had the opportunity to come into effect.

Let \( C_{u,i} \) be the cost of an unplanned LRI rejection due to component \( i \), \( C_{p,i} \) the cost of a planned LRI rejection due to component \( i \), \( C_{h,i} \) the cost of replacing component \( i \) at time \( t \), \( f(t) \) the probability density function of time to failure (TTF) for component \( i \), \( f_i(t) \) the probability density function of TTF for LRI (excluding component \( i \)), \( T_s,i \) the soft life for component \( i \), and \( T_{h,i} \) the hard life for component \( i \).

Using simple probability arguments, one can derive the following mathematical expressions. The expected costs associated with unplanned engine removals caused by the given component, \( E(C_{u,i}) \), is given by:

\[
E(C_{u,i}) = H(T_{s,i})C_{u,i} \quad \text{for} \quad 0 < t < T_{s,i}
\]  
(1)

where \( H(t) \) is the cumulative hazard function given by:

\[
H(t) = \int_0^t h(x) dx = \int_0^t \frac{f(x)}{R(x)} dx = \int_0^t \frac{f(x)}{1 - F(x)} dx.
\]  
(2)

For the case where the distribution of the times to failure for component \( i \) are given by a Weibull distribution, \( W[\beta, \eta] \).

\[ H(t) = \left( \frac{t}{\eta} \right)^\beta. \]

The cumulative hazard function, \( H(t) \), is used here rather than the cumulative distribution function, \( F(t) \), as it is assumed that a component which fails before it reaches its soft life will be repaired to a “same-as-old” state and hence can fail several times before eventually reaching its soft life. If the repair restores the component to a “same-as-new” state then \( H(t) \) should be replaced by the renewal function with the cumulative distribution function of TTF given by \( F(t) \).

The expected cost for the period when the component’s age is greater than its soft life but less than its hard life can be derived in two parts: the first is when the LRI is rejected before the component; and the second when the component fails before the LRI. In both cases, the component would be replaced with a new one, so there would be no opportunity of it failing two or more times, within this period. The corresponding expression is given by:

\[
E(C_{p,i}) = C_{p,i} \int_{T_{s,i}}^{T_{h,i}} f_i(t)(1 - F_i(t)) \, dt + C_{u,i} \int_{T_{s,i}}^{T_{h,i}} (1 - F_i(t))f_i(t) \, dt \quad \text{for} \quad T_{s,i} < t < T_{h,i}.
\]  
(3)

In Eq. (3), \( f_i(t) \) is the convolution of \( f_j(t) \) for \( j = 1, n \) and \( i \neq j \) where \( n \) is the number of components which can cause an LRI failure. Similarly for \( F_i(t) \).

The expected cost of a planned LRI removal due to the component reaching its hard life is given by:

\[
E(C_{l,p}) = R(T_{h,i})C_{p,i} \quad \text{for} \quad t > T_{h,i}.
\]  
(4)

where \( R(T_{h,i}) \) is the reliability function for component \( i \). If the component reaches its hard life, the LRI is removed and the component is replaced with a new one.

Now, the total expected cost of maintenance is given by:

\[
E(C_i) = E(C_{u,i}) + E(C_{s,i}) + E(C_{l,p}).
\]  
(5)

It will be noted that \( E(C_{u,i}) \) is a function of \( T_{s,i} \), \( E(C_{s,i}) \) is a function of \( T_{s,i} \) and \( E(C_{l,p}) \) is a function of \( T_{h,i} \). Thus, by taking partial derivatives of Eq. (5) with respect to \( T_{s,i} \) and \( T_{h,i} \) and equating them to zero, the optimum values of these can be found such that they minimise the total cost, i.e.:

\[
\frac{\partial E(C_i)}{\partial T_{s,i}} = 0 \quad \text{and} \quad \frac{\partial E(C_i)}{\partial T_{h,i}} = 0.
\]

Note that in these equations, it has been assumed that the component has only one failure mode. It should also be noted that, when the system has been recovered, the ages, of the various components within it, would not all be zero following such a recovery. Thus, the optimum soft and hard lives may need to be re-evaluated after each system recovery, taking into account the respective ages of all of the components which may cause a system failure.

If component \( i \) causes an LRI removal (fails or reaches its hard life), it will create an opportunity for the other components that have soft lifing policies; thus the costs \( C_{u,i} \) and \( C_{p,i} \) will depend on these other component soft lives (and, of course, vice versa). Similarly, there will be an opportunity to inspect other components for unexpected damage, wear or corrosion, that may have occurred before the component has reached its own soft or hard life and hence may avert a failure.

For safety-critical components, the hard life is determined by its failure distribution(s) and is not subject to economic considerations, in the same way as non-safety-critical ones. However, the soft life, usually referred to as the minimum issue life or MISL, is based purely on economic considerations and is subject to the above analysis.

If a component has several failure modes the whole process gets somewhat more complicated. It is possible that if the component fails due to failure mode \( i \), it will be repaired to the same-as-old whereas if the cause was failure mode \( j (i \neq j) \), then the component is replaced or restored to same-as-new. The component, which failed due to mode \( i \) could fail again for the same reason or fail due to a different (competing) failure mode. The amount of damage (to other components) may also be significantly different if the component fails in different ways. As an example of this, a blade can melt if its cooling holes become blocked, or it can break off at its root. If it melts, the amount of damage to other components is minimal but if it breaks, the damage can be extensive.

A further complication is that different soft lives (and MISLs) may be applied at different echelons in the maintenance environment. Typically, components held (in storage) at the deeper echelons (third and fourth lines) will be required to have potentially more life remaining.
(before causing a planned LRI removal) than those which are held at second line. A typical second line MISL might be 100 h whilst the third or fourth line MISL might be 400 h. This is generally due to the fact that the second line MISL would normally only apply to modules which have not had to be recovered, i.e. they have simply been removed for access to other modules which have had to be recovered. Modules held at the third or fourth line would normally only be there if they have been rejected and hence would have needed to be recovered. To put it another way, if a module contains rejected components and hence has to be stripped and re-built then the marginal cost of replacing a hard or soft lifed component is relatively low compared to the case when the module is rejected purely to replace such a component.

Secondary or caused damage is often of a stochastic nature. The amount of damage caused by the failure of a component may be related to the “spool” speed (and hence the centrifugal forces acting), the temperature of the components it may hit and “luck” (as to whether it actually hits anything or simply passes through the gaps). If it hits a component hard enough, it could cause it, or a part of it, to detach, giving rise now to two or more objects passing through the engine. Similarly, if the component(s) it comes into contact with are themselves already damaged, worn or corroded, then the probability of them breaking is likely to be significantly higher.

3. Case study on an aero-engine

A simulation program was coded to consider a very simple case in which the LRI (Engine) arisings are modelled by an MTBF and just one part is considered for soft/hard life optimisation. The MTBF for the engine should be adjusted to exclude the failures resulting from this part, which is modelled using a Weibull distribution. No attempt has been made to model either the maintenance or supply activities—recovery of the LRI is instantaneous and the component in question is also instantly replaced by a new one every time it is rejected (for whatever reason). Suppose the MTBF for an engine is 1000 Flying Hours (FHrs) excluding component 1 which has a Weibull time to failure distribution with scale parameter 5000 h and shape parameter 3 (i.e. W[3,5000]).

Let the cost of an engine failure (and recovery) due to: an unplanned failure of component 1 \( (C_u^i) \) be 100, and a planned rejection of component 1 \( (C_p^i) \) be 50.

Let the cost of replacing Part 1 (soft-lifed) \( (C_{s,l}^i) \) be 10.

[Note: the (expected) cost of an “unplanned failure” would include the cost of repairing the failed component and any others that were either secondary or found damaged or that had exceeded their soft lives or MISL. The (expected) cost of a “planned rejection” would include the cost of replacing the component and any others that were found damaged or that had exceeded their soft lives or MISL. It would not include secondary damage because the component had not failed and so could not have caused any.]

Using Monte Carlo simulation with 1000 replications of one engine flying 10,000 FHrs the following three graphs were produced.

Fig. 1 shows how the costs vary with hard and soft life. This indicates that there is no benefit in setting a hard life—all curves are decreasing monotonically (allowing for random variations) as the hard life increases.

Fig. 2 shows how the recovery cost varies as the soft life increases for an infinite hard life. It appears to become asymptotic to a value of approximately 157,000. Due to run times and the fact there was considered to be little benefit, soft lives between 4900 and 10,000 were not simulated (hence the straight line).

Fig. 3 shows how the numbers of unplanned engine rejections due to component 1, “Failures”, and the number of soft-lifed removals of component 1, “Soft Lifed”, vary with the soft life.

It should be noted that if the engine fails for reasons other than the failure of component 1, it has been assumed that
component 1 is not replaced unless it has exceeded its soft life. In practice, there is a certain probability that the part would be damaged as a result of the primary cause of failure. There is also a certain probability that the component will be found damaged during inspection while the engine is being stripped. This may actually be age-related; unfortunately, we have no data to be able to test this hypothesis.

In this particular exercise, the failed engine was recovered instantly and continued to operate until it either failed again or achieved 10,000 FHrs. No attempt was made to model spares or the recovery procedure. In practice, when an engine fails it is replaced by a spare (as soon as one becomes available). The failed engine is stripped to its modules. The rejected modules are replaced with spares and are sent for part exchange. The fact that the parts will not need to be inspected, which often involves removing their coatings, the use of dye-penetration and being recoated (if found satisfactory) all by relatively skilled personnel, means additional savings may be made. Strictly, this only applies to parts that have exceeded their soft life; as there is no point in inspecting a part if it is going to be replaced regardless. However, if the part has not yet reached its soft life, which from the graphs is around one-third of the expected life (1500 versus 4500) there is unlikely to be any sign of sub-surface damage.

4. Conclusion

Soft and/or hard-lifing may have some serious repercussions, which will need to be carefully considered before implementation is authorised. Currently, some military engines are rejected relatively frequently, but if all of the prime drivers are given soft or hard lives, that frequency is likely to be significantly reduced. Although this sounds an ideal situation, it does however mean that many components that would normally be inspected regularly may stay in the engine for much longer between such inspections and hence could cause (additional) engine failures.

The above is based on the assumption that the time-to-failure distribution parameters are known. In practice, this is seldom the case, at least at the time the engine enters into service. It is only with good in-service data that confidence in the a priori estimates can be gained, or new estimates
made. If the soft-life has been set based on inaccurate estimates, the value may no longer be optimal—if too high then there will be too many failures, and if too low, too much potential component life may be discarded. The fact that the curve in the example is relatively flat in the region of the optimum suggests that it is probably insensitive to small variations in the parameters. This, however, would need to be checked before implementation.

At present, unless a particular type of component starts to cause unexpected engine failures (due to it failing either at much lower ages than expected or in a way that had not been anticipated), there is likely to be very little accurate data on the times-to-failure. Parts life-tracking is generally only done on safety-critical components. It may, by making various assumptions about the component’s history, be possible to get a reasonable estimate of the age at the time of failure but this is a tedious and expensive procedure so is not normally performed (except for the reasons given above). Electronic tagging of components may, in future, make parts life-tracking a feasible option.

During a normal engine recovery, many parts are rejected following their inspection. These rejections may be as a direct consequence of the primary cause of the engine failure (caused or secondary damage), or it may be quite independent (found damage). Until a soft-lifing policy is introduced, it will not be possible to determine how much found damage may be avoided, as it is not currently known how much of this is age-related.

Safety-critical components are usually given both a hard and soft life (the latter more commonly referred to as a minimum issue life (MISL). With fewer engine removals, more of these parts will reach their hard life that has the positive benefit that less potential (component) life is lost. However, it has a potential cost insofar as more will stay in the engine for longer and hence will increase slightly the risk of a serious engine failure. The hard life limit is set without reference to any MISL that may be applied, so this should not cause a problem. For components which are deep inside the engine, their (soft life) removal may require a greater depth of strip than might otherwise be the case. This would not only increase the (strip and rebuild) costs but could also expose components that would not otherwise have been inspected; and may increase the amount of maintenance induced failures, although at present, this is not a “recognised” cause of failure/rejection and so is not monitored.

One advantage of this approach is that by reducing the number of unplanned LRI removals, it should become easier to meet any maintenance-free operating period (MFOP) [4] requirement. Essentially, an MFOP is a rolling warranty. The operators require the manufacturers or contractors to "guarantee" that no unplanned arisings of their LRI’s will occur in given periods of operation.

Although the example is a gross simplification, and the costs at least, have no meaning, nonetheless there does appear to be a potential benefit from setting soft lives on relatively cheap components that can cause expensive, unplanned, engine rejections. To determine the optimum soft lives will need a much more sophisticated model than the one used for this exercise. It will also require an efficient optimising algorithm—probably Genetic Algorithms or Tabu Search. The example took about 10 h to produce the graphs shown, using a full grid search for just one part.

As engine monitoring systems become more sophisticated, ages and lives may be measured and stated in (stress) cycles if it is found that these are a more accurate measure of the times to failure, as has been found to be the case with safety-critical parts. These costs will need to be considered if soft-lifing is the only reason for incurring them.

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