Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)
Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio
©2023 ESREL2023 Organizers. *Published by* Research Publishing, Singapore.
doi: 10.3850/978-981-18-8071-1_P563-cd

There is no superior maintenance style in asset management

Aart-Jan de Graaf

IWO, Institute for Science and Development, Ede, The Netherlands. E-mail: aj.degraaf@iwo.nl

Robert Ross

IWO, Institute for Science and Development, Ede, The Netherlands. E-mail: r.ross@iwo.nl

Goal of this paper is to provide a comprehensive overview of the considerations that drive the decision for a preferred maintenance style. Underlying statistical analyses are provided by given references to earlier published work. Reliability and risk-based considerations affect the maintenance style for asset management during the operational life of a system of assets. Performance and reliability assessment of assets are driven by probabilistic and distribution function oriented analysis based on failure data statistics and condition monitoring. Highly reliable, capital-intensive and long-living components usually provide very small datasets collected from accelerated aging tests and field data which make predictions of future failure times difficult. Capital-intensive power-electronic components increasingly gain an important role in power networks and replacement should be scheduled carefully. Therefore, there is an increased need for prognostics and health management also for power electronic systems in order to prevent unplanned failure series.
A framework is presented to assess different maintenance styles on the basis of a common framework and in relation to (partially redundant) system configurations and the available resources for repair or replacement. Eventually, public-private context-driven values, backpropagated to the assets expressed in terms of Health Indices, Risk Index and possible other Asset Indices, determine which maintenance style is most effective and affordable.

Keywords: Reliability, Risk, Hazard rate, Maintenance, Asset management, Prognostics, Health Management.

1. Introduction

Condition-based maintenance (CBM) is currently considered as more suitable than period based maintenance (PBM) and corrective maintenance (CM). CBM prevents loss of useful life of assets that would be replaced too early in case of PBM. CBM prevents cost of unplanned down-time and maintenance in case of CM. In addition, data-driven or AI methods could be used to reinforce the expert rules used by asset managers for maintenance decisions.

This paper is written to promote a more balanced comparison of well-known maintenance styles: PBM, CM, CBM, RBM (risk-based maintenance). Clarity is encouraged by introducing an assessment framework that is more comprehensive as it takes into account corporate values as well as cost and availability of resources (e.g. personnel) needed for maintenance. Monitoring of individual assets can have a substantial impact on costs of resources and availability of resources can limit inspections. Corporate values (such as, performance, safety, finances, reputation, customer satisfaction, environment, compliance, social responsibility) have to be full-filled. At the same time costs have to be minimized while considering the limitations in availability of personnel, minimum duration of asset replacement and availability of spare parts.

Too much emphasis on reliability of individual assets without considering the wider context of their place in a system configuration and their specific contribution to corporate values could turn out to be an unnecessary expensive or unfeasible approach. The electrical power networks sector with assets that have a very long useful life (typically 40 years), provides convincing examples for this statement.

It stays necessary to use a statistical life-time model based on failure distribution functions as assets affect corporate values individually or collectively depending on the system configuration.

2. Background

Enhancing reliability of Electronic Components and Systems (ECS) is optimizing characteristics of a system in a particular (usually undetermined) phase of the life cycle. ECSEL JU European Project “Intelligent Reliability 4.0”, iRel40 (2023), rephrases this objective to enhance and ensure reliability of ECS by reducing their failure rates along the entire value chain.

Power networks gradually integrate capital-intensive power-electronic components (e.g. in HVDC-links) and servicing and replacement should be carefully considered if not for the investment, then for the value their functioning represents. The long lifetime of components, the availability of servicing crew (lack of personnel) and the complex logistics of large pieces of material (e.g. large power transformers) require a proactive and prognostic approach based on statistical knowledge of failure behaviour of components and the system configuration.

Unfortunately, a value chain focus with emphasis on component reliability is too restrictive for a systems oriented view. The random failure dominated lifecycle phase is the primary operation and maintenance phase that justifies the existence of a system. System operation and maintenance activities (inspection, servicing and replacement of components) also affect the reliability of ECS at the system level. E.g., replacement of a component can be viewed as servicing of the system.

But this does not automatically point out what is the best choice for a maintenance style (corrective, period-based, condition-based, and risk-based; see also section 4). Historically, components were considered to be consumables suitable for corrective maintenance (run-to-fail, replace-to-restore system operation). A domestic example is the practice of exchanging light bulbs on failure generally without considering preventive maintenance on individual lightbulbs.

Obviously, the reliability of ECS at component level is a pre-requisite for achieving reliability targets at system level. See for instance Rausand (2014). Therefore maintenance is of importance. Other considerations based on corporate and public values however, may also determine what is the most effective maintenance style and what activities should be considered, and under what condition be scheduled. Corporate and public values encompass values like health, safety, environment, reputation, service provided and monetary.

Attention is paid to the bottom part of the hazard rate bathtub curve (dominated by random failure processes): “the range that covers most of the operational life, where maintenance style, repair and system configuration largely determine the system performance”. Ross (2022b). Operational life (of the system) can be extended by repair or replacement of components in order to reset the wear-out process and keep the system failure rate and availability at acceptable levels. Such systems with a more or less flat (=constant) hazard rate behave as if their failure is random.

We assume quality control to have dealt with teething issues (also called ‘child mortality’) and that the final stage of wear-out has not yet been reached. But even teething (with burn-in testing) is still under study and may be improved by informed sampling and conditional burn-in tests to avoid negative effects on components that passed an accelerated aging test Baraldi (2021), Yousefian (2022).

Kurz (2017) explains nicely the difference between a quantitative approach, i.e. fitting a lifetime distribution to (censored)failure times recorded from reliability testing, and a qualitative approach, i.e. a failure probability that is estimated based on the observed number of failures within a test sample set. But it is important that the failure distribution functions are known and can be used to proactively manage the occurrence of failures by maintenance activities that change the failure distribution. This maintenance strategy is called Prognostics and Health Management (PHM), Farsi and Zio (2019), Ross (2022b). PHM will most likely adopt a mix of maintenance styles as already pointed out by Ross (2017).

3. Maintenance – activities and styles

Maintenance activities are needed to ensure that a system of assets will meet the quality and performance requirements during the full utilization stage of the system lifecycle. Activities (inspection, service and replacement) are required to determine and restore the performance, condition and other properties of the assets. Ross (2019a).

Inspections collect required information about the technical condition and functional performance of assets. Servicing prolongs the operation life and restores or improves the condition of assets. Replacement ends the lifetime of one asset and installs another asset to pursue the functionality of the retired asset.

Repair, refurbishment and overhaul could be seen as intermediate forms between servicing and replacement. It depends on the definition of assets: what systems, subsystems, components, or parts are valuable enough to be taken as assets.

Four different maintenance styles can be distinguished: corrective (CM), period-based (PBM, also called time-based TBM if the periods are fixed times), condition-based (CBM) and risk-based (RBM) maintenance. These are briefly explained below. A more versatile description, amongst many, can be found in section 9.1.4.2 of Ross (2019a).

CM runs an asset until it fails. Repair or replacement if needed to restore its function. PBM follows a scheduled plan to service assets to prevent occurrence of failures. Replacement of assets takes place before a significant failure probability arises. CBM monitors the condition of individual assets in order to service or replace when needed. RBM is similar to CBM but instead of asset condition, the asset contribution to corporate values is considered. Individual assets of the same type may have a different contribution to corporate values because of their specific location.

Different terms exist (e.g. preventive and predictive maintenance). But there is a clear way to relate these terms to the four maintenance styles above. For example, predictive maintenance employs similar kind inspections and monitoring activities as condition-based maintenance. Preventive maintenance corresponds to period-based maintenance as it uses the same kind servicing and replacement.

The maintenance style will be affected by the possibilities and limitations of diagnostics to monitor the wear-out condition of a component or the ability to classify a component to early wear-out- or normal components. Also the availability of work forces may determine the maintenance style. The optimization of the mix of maintenance styles is subject of Reliability Centered Maintenance. Ross (2022b).

The presence of redundancy in a configuration does not make it obvious which maintenance style is most effective: “An important conclusion is that even in the absence of failures an unwanted situation may build up where redundancy is not effective anymore”. Ross (2019b).

4. Assessment framework

For this, a framework is proposed and presented to obtain a consistent and objective relationship between the observed corporate values and the actions performed to maintain their proper levels. Application of this framework is evaluated using examples originating from the field of power systems. The examples illustrate the role of fault detection, diagnostics and subsequent prognostics in relation to the maintenance strategies and the intended contribution to the corporate values.

Figure 1. Chain of elements considered.

The framework is built upon a simplified structure in which the corporate values are linked by a chain of elements that end at needed resources (Figure 1). Examples are provided for the sake of clarity with elements from the industrial sector electric power grids.

Corporate values are realized (in positive or negative sense) by various functions (supply of power, occupation of space, support of confidence, emission of noise, control of hazards) that depend on assets (components, cable sections, cable joints, switch gear, measuring- and power transformers).

The assets may be arranged in parallel circuits that form redundant configurations controlled and protected by secondary systems. Thus leading to a complex relationship between several assets and the functions used to fulfil the various corporate values.

Maintenance actions may be scheduled (periodically or based on generated condition alerts) and performed to ensure that the assets keep up with the desired performance and reliability levels. These levels can depend on the asset’s contribution to the corporate values. This dependency between assets and the corporate values is put into a Health Index Model (Figure 2). Cigré (2010), Ross (2017). Actions depend on suitability of required resources.

The use and preparedness of the resources in itself does also have direct impact to some of the values (e.g. financial, human capital). Moreover, the (lack of) availability of resources can also be a reason to reconsider an established maintenance style.

Eventually, the asset condition is represented by a failure distribution function usually indicated by a Hazard rate explained in the next section. Additional inspections and condition monitoring of an asset would be used to make an individual assessment that leads to a condition indicator.

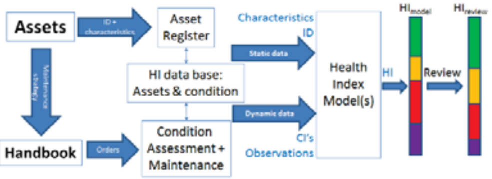

Figure 2. The concept of the health index in Ross (2019b) p12. Dynamic data is based on observations that are translated into condition indicators (CI).

5. Mixed distributions and redundant circuits

A system configuration with several components in partly redundant configuration will reveal different failure behaviour depending on the used assets and the various failure mechanisms.

Each failure mechanism and each subpopulation of components of a considered set of assets is modelled using the Weibull distribution function and the corresponding Hazard rate function h_{Wb}.

$$h_{Wb}(t) = \frac{f(t)}{R(t)} = \frac{\frac{\beta}{\alpha^{\beta}} \cdot t^{\beta-1} \cdot e^{-\left(\frac{t}{\alpha}\right)^{\beta}}}{e^{-\left(\frac{t}{\alpha}\right)^{\beta}}} \tag{1}$$

This is a conditional distribution density function expressed by the ratio of the unconditional distribution density function and the reliability function. In this two-parameter function, α represents the scale or expected value of the failure time, and β represents the shape for one of the three types of processes: teething ($\beta < 1$), random-failure ($\beta = 1$), and wear-out ($\beta > 1$).

5.1. *Elementary Hazard rate*

The Hazard rate of an elementary component and process follows a Weibull distribution if a weakest link model applies to the failures. The hazard rate in Eq.(1) is simplified to:

$$h_{Wb}(t) = \frac{\beta}{\alpha^{\beta}} \cdot t^{\beta-1} \tag{2}$$

It will be used as a primitive to construct synthesized and composite Hazard rates for competing processes and mixed populations.

5.2. *Competing processes*

The corresponding Hazard rate of the three competing processes (teething, random and wear) provides the Bath tub shape (Figure 3):

$$h_n = h_t + h_r + h_w \tag{3}$$

Here, h_n is the summed (normal) hazard rate, h_t is the hazard rate due to teething, h_r due to random failure and h_w due to wear.

Burn-in tests will typically be used to eliminate components that suffer from the teething phase and, hopefully, the remainder will be dominated by acceptable random failure rates and wear-out near designed end-of life stage.

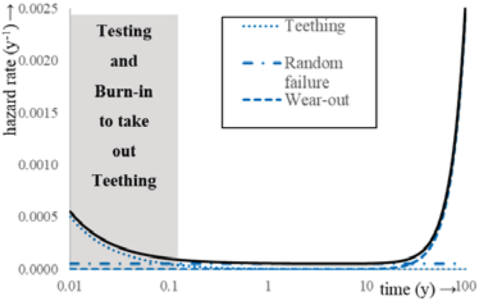

Figure 3. The sum of the hazard rates of competing processes forms the famous Bath tub shape. h_t: $\alpha = 0.008, \beta = 0.000005$; h_r: $\alpha = 20000$, $\beta = 1$; h_w: $\alpha = 200$, $\beta = 4$.

5.3. *Two distributions*

Unfortunately, assets can be taken from a series of components with a weak sub-population. This can be caused by an unforeseen effect of a modification in the products or a manufacturing process or by imperfect installation. This is likely to be observed when components are taken into operation and early failures are discovered after an initial period without failures (Figure 4).

It is paramount that the ratio $p_d : p_n$ between defective and normal components should be small and the remaining defective parts should vanish from the population.

$$h_{mix} = \frac{p_n \cdot h_n \cdot R_n + p_d \cdot h_d \cdot R_d}{p_n \cdot R_n + p_d \cdot R_d} \tag{4}$$

Here, h_{mix} is the resulting hazard rate of the mixed normal and defective sub-populations, h_d the hazard rate of the defective sub-population, p_n and p_d the fractions of normal respectively defective products, R_n and R_d the reliabilities of the normal respectively defective products. The Hazard rate of the mixed distribution reduces to the normal population when the fraction of defective products gets depleted.

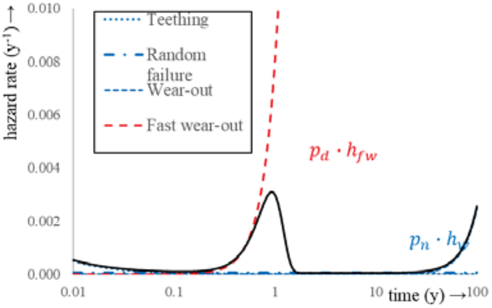

Figure 4. Mixed distribution with an additional sub-population having fast wear-out $p_d = 0.002$; $p_n = 1 - p_d$; $h_d = h_{fw}$: $\alpha = 1$, $\beta = 4$; and h_n as defined in Figure 3.

5.4. *Period-based or condition-based service of wear-out parts*

Components with serviceable parts that suffer from wear-out processes, can benefit from period-based or condition-based maintenance to eliminate (or reset) the increasing hazard rate of this process (Figure 5). Examples are replacing worn contacts by new contacts in switchgear, replenishing oil in pressurized oil cables or restoring pressure in gas-insulation switchgear (GIS). However, in reality, it may not be possible to reset all wear by servicing. In such cases, the non-serviceable wear will ultimately drive the hazard rate to high levels and servicing may no longer be worthwhile.

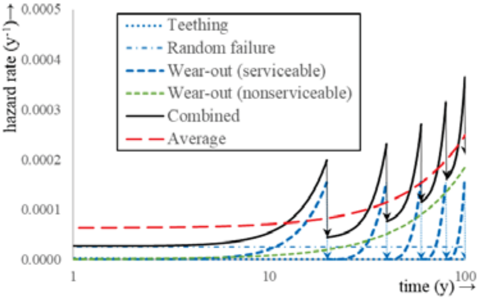

Figure 5. Period-based maintenance of serviceable parts resets part of the wear-out processes (maintenance interval is 20 years).

5.5. *Redundant circuit associated distributions*

Assets may be arranged in parallel circuits to form redundant configurations. This measure is used to eliminate system functional failure caused by a single component failure (provided faults are statistically unrelated, which would e.g. not be the case with common-cause failure).

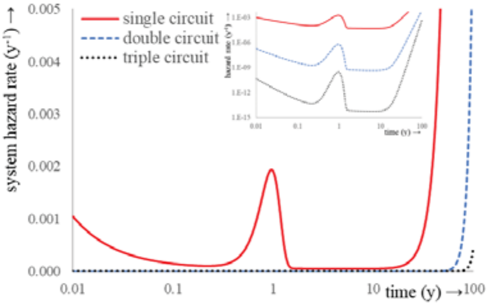

Figure 6. Effect and limitations of parallel circuits (redundancy) to system hazard rate. The inset graph uses a log-log scale to illustrate the multiplier effect of redundancy.

Figure 6 illustrates the effective reduction of the failures rate by parallel circuits. Whenever a single circuit does not meet the required reliability, a redundant circuit may be appropriate. It also demonstrates the additional robustness in case of some teething and the presence of a subpopulation with early wear-out. A more thorough treatment and rationale can be found in Ross (2022a).

Care must be taken near the end of life of the components, though. The wear-out process quickly reduces the multiplier of reliability in the parallel circuit. A second circuit failure could follow a first failure more rapidly than expected. If a second failure occurs before the first circuit is repaired the system itself fails which causes a black-out.

A positive characteristic of parallel circuits of equal components is that failure data can be collected of components while circuits still perform their intended function. This provides very relevant input to estimate or update the failure distribution data of the population of components. Ross (2022c) illustrates that this may be needed to support critical decision making. A good introduction to parameter estimation of distribution functions based on failure data is available. ReliaWiki (2023).

6. Examples

Examples illustrate that each maintenance style has beneficial and adverse effects. Therefore, a single maintenance style may not be optimal to meet the corporate values.

Period-based maintenance should reset the wear-out phase. The interval for servicing or replacement is equal for all components of the same type. This implies that the weakest component of the group limits the period. Other members of the group may be sound enough to be used with longer intervals in the servicing cycle. The limited demand of personnel and the ability to schedule the maintenance activities well ahead is the biggest advantage of period-based maintenance.

Corrective maintenance is preferred when preventive efforts and costs are higher than unexpected failures with consequences and repair. Redundant connections (double or even triple circuits) using secondary equipment to detect single faults would be used to maintain a required reliability- and availability level for the connection.

There are limits to the number of maintenance crews available that ensure maintenance preparedness required for restoring redundancy in the network Ross (2022a), Ross (2019b). An important consideration is the random characteristic of failures. It may be the case that urgent repair is required to restore redundancy of the connection. The risk of failure of a single circuit connection may be unacceptable.

Condition monitoring could be used to detect the expected increase of hazard rate associated with a wear-out process. This requires first of all a diagnostic that is able to measure a quantity that is related to the hazard rate or decreased remaining life. An example can be measuring the humidity or acidity of transformer oil. Another example is an observation of partial discharges in an insulation system. However, observations only become informative if they can be interpreted and quantitatively related to a probability of failure in a given time. Diagnostics capabilities require expert rules to become truly valuable.

In some cases monitoring systems have a shorter or comparable life expectancy. It may be required to extend PHM to the condition monitoring system itself. E.g., the life-time of a fibre optic distributed temperature sensor may be 15 years, whereas a power component like a cable may have an intended service life of 40-50 year. If the optical fibre cannot be replaced after malfunction, the cable has lost the capability of monitoring the respective condition.

Condition-based maintenance finds its added value in the opportunity of servicing and replacement of individual components. The lifetime of other components could be extended. But, lack of personnel may be problematic for conducting the required inspections, monitoring and diagnostics for CBM.

Partial discharge detection is often used to monitor the condition of the insulation of a high-voltage cable. The method of monitoring or inspection typically requires modifications to the circuit and has to take the cable out of operation. It therefore introduces additional risk of servicing failures.

Reliability oriented maintenance puts limits to the hazard rate of components of a specific type. However, the specific location of each component and its known failure modes contribute differently to corporate values (especially for the case of safety, environmental and social acceptance).

Corrective maintenance in the form of replacement could utilise assets more economically then period-based preventive replacement, because the latter wastes some life. However, the unavailability due to unexpected replacement may have resulted in more collateral damage, the cost of unplanned maintenance is usually a multiple of planned costs and may take too long. Being prepared for unplanned replacement may also require a larger stock of spare parts and adequate logistics, which the more challenging if such parts are capital intensive.

7. Conclusions

Inspection, fault detection, diagnostics and prognostics at component and subsystem levels will contribute to quantitative assessment of performance and other properties of system and application level functions that can be linked to a multidimensional impact-space specific for the organisational context. The public-private context-driven weights of this impact-space, or Health Indices, determine to a larger extent which maintenance style is most effective and affordable. An optimum maintenance mix can be strived for by considering the performance, costs and risk appetite, which is usually part of the domain of Reliability Centered Maintenance. It should be noted that currently human capital restrictions (lack of personnel) may limit the necessary inspections or preventive service activities. Lack of inspections being carried out, effectively changes CBM to CM. In that case PBM would be less labour-intensive and more appropriate than imperfect CBM. If the claim on knowledgeable workforce becomes a bottle-neck, then human capital indicators must be involved into the equations to optimize PHM.

The many considerations that likely lead to different mixes of maintenance is the main reason to state that there is no superior maintenance style, but the optimum depends on many factors. But with a given set of boundary conditions of requirements and capabilities, an optimum of maintenance, redundancy and repair strategies should be developed.

Acknowledgement

The research for this work received support from the EU H2020 R&I program and NL Min. of Economic Affairs and Climate under ECSEL grant agreement No 876659 (iRel4.0).

References

Baraldi, P., Medici, S., Ibrahim, A., Zio, E., Lewitschnig, H. (2021). A Method based on Gaussian Process Regression for Modelling Burn-in of Semiconductor Devices. In, *Proceedings of the 31st European Safety and Reliability Conference,* Research Publishing, Singapore.

Cigré Working Group C1.16. “Transmission Asset Risk Management” (Cigré TB 422, 2010).

Farsi, M.A., Zio, E. (2019). Industry 4.0: Some challenges and opportunities for Reliability Engineering, *International Journal of Reliability, Risk and Safety: Theory and Application, vol.2019*

Kurz, D., Lewitschnig, H., Pilz, J. (2017). Failure probability estimation under additional subsystem information with application to semi-conductor burn-in. In, *Journal of Applied Statistics, vol 44,* Taylor & Francis.

Rausand, M, (2014). *Reliability of Safety-Critical Systems*. Hoboken, NJ: Wiley

Ross, R. (2017). Health index methodologies for decision-making on asset maintenance and replacement. In, *Cigré 2017 Colloquium of Study Committees A3, B4 & D1,* Winnipeg, Canada.

Ross, R. (2019a). *Reliability Analysis for Asset Management of Electric Power Grids*. Hoboken, NJ: Wiley-IEEE Press.

Ross, R. (2019b). Asset Replacement Strategies in Ageing Grids: Periodic Maintenance vs. Condition Based, In, *Proceedings of the INMR World Congress, 2019*, Tucson, Arizona.

Ross, R. (2022a). Diagnostics, Maintenance & Replacement Strategies Applied to Insulators & Cable Systems. In, *Proceedings of the INMR World Congress, 2022*, Berlin.

Ross, R. (2022b). Prognostics and Health Management for Power Electronics and Electrical Power Systems. In, *Proceedings 9th International Conference on Condition Monitoring and Diagnostics 2022*, Kitakyushu.

Ross, R. (2022c). Weibull Analytics of Observed and Suspended Failure Data. In, *Proceedings 9th International Conference on Condition Monitoring and Diagnostics 2022*, Kitakyushu.

Tijerina, M.B., Pina-Monarrez, M.R., Escalante, A.Y.R. (2023). Reliability Engineering Opportunities in Industry 4.0, *Engineering Today*

Yousefian, P., Randall, C.A. (2022). Determining the effect of burn-in process on reliability of X7R multilayer ceramic capacitors. In, *Journal of Materials Science, vol 57, pp 15913-15918*, Springer Nature

iRel40, Intelligent Reliability 4.0, URL https://www.irel40.eu/, last checked: 30 January 2023.

ReliaWiki, "Parameter Estimation," ReliaWiki, URL http://www.reliawiki.org/index.php/Parameter_Estimation, last checked: 28 April 2023.