Replacement CapEx from Conceptual and Practical Perspectives

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Abstract

In an infrastructure business the key competitors for capital expenditure are growth and replacement. In many infrastructure businesses, and cetainly in the electricity sector, replacement capex is becomming the key driver. In this paper we show from a conceptual perspective that the core problem to solve in identifying efficient replacement capex is the translation of component condition to failure hazard and demonstrate, through two case examples, means to deal with this problem.

1 Introduction

This paper accompanies a presentation by the author to the Infrastructure Capex Summit at Auckland, New Zealand, in November 2008. The presentation proposes that the core problem to solve in identifying efficient replacement capex is the translation of component condition to the failure hazard of that component. The conceptual process used is to define efficient replacement in terms of the risk costs of future failure if replacement is not undertaken and show that reduction in the dispersion of the risk is the key driver in determining the economic viability of replacement at any particular time. It is then argued that assessment of component condition achieves this reduction in risk dispersion and hence the case for preventive replacement achieves economic efficiency. This may be measured and used provided the condition assessments can be translated into probability of failure.

That undertaking condition assessments on assets is a good way of assessing asset risk is a statement of the obvious to any asset manager. The power of understanding this process within a conceptual framework is it enables quantifiable decisions about replacement and lends itself to extension. This is demonstrated through two case studies. The first looks at using weighted condition scores on power generators components to understand the risks from this fleet of assets. This case study demonstrates a method of translating component condition into failure hazard. The second case study looks to measure the value of changing to an improved but more expensive condition assessment test on wooden power poles. This case study uses the conceptual framework to understand the value of better information.

Table 1: Meaning of Terms

Term	Meaning
failure	functional failure of the component necessitating replacement
hazard	probability of failure in the next time interval (usually 1 year) given it is functional at the beginning of the time interval
component	a physical object, that may itself comprise sub-components, for which a condition assessment may be made; a component is a physical construct and may have multiple failure modes
asset	a group of components from which the serviceability of the group derives business value; an asset is a business construct
risk	within a time interval, the failure hazard times the expected consequence cost of that failure
condition	the relationship between the actual strength of the component and the design strength required of the component in that asset

This paper seeks to provide a conceptual understanding of the issues discussed. Mathematical derivations are not provided and some of the models presented have been simplified to aid understanding. However, some of the terms used have specific meanings as given in table 1

2 Efficient Replacement

We assume here that replacement of a failed component or asset is undertaken as an imperative and assume that replacement is the correct decision as opposed to, say, abandon the asset an undertake the business in a different way. In other words, we do not consider allocative efficiency. We take the position that the replacement is efficient if we undertake replacement at a time (T) that minimises the present value of the replacement plus the accepted risk of failure less the avoided risk of failure. The situation is illustrated in figure 1. Note that we are assuming like-for-like replacement; replacement with a more (or

Figure 1: Risk and Replacement Timing

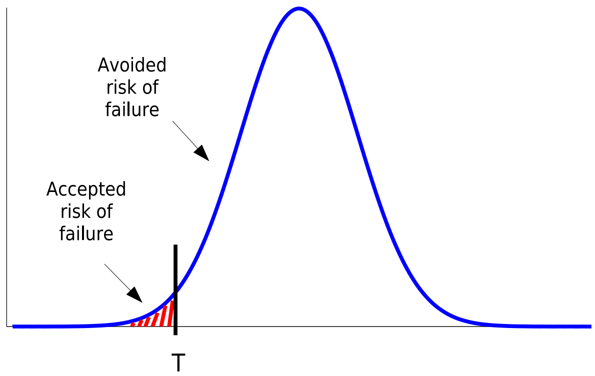
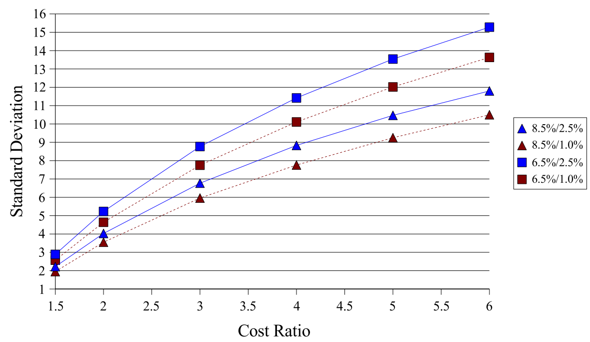


Figure 2: Dispersion vs Cost Ratio for Zero Present Value



less) productive asset can be readily included but is avoided here for simplicity.[1]

If we assume a failure distribution type, for example a normal distribution, and select a target level of acceptable risk, for example 1%, then we can rearrange the present value equations and numerically solve for threshold curves that relate the dispersion of risk (measured by the standard deviation of the distribution) to the ratio of the cost of failure to the cost of preventive replacement ($F = Cf/Cr$). Figure 2 illustrates such curves for a normal distribution showing two levels of threshold risk (1% and 2.5%) and two levels of weighted average cost of capital (WACC real, post-tax of 6.5% and 8.5%).

For preventive replacement to be economically viable, the intersection of the cost ratio and the dispersion of the risk must plot below the curve of selected risk threshold and cost of capital. While such curves might be useful in themselves, [2] this chart serves to illustrate a key point; the economics of the decision is *not* a function of the expected time to failure. The expected time to failure (the mean of the failure distribution) gives us information about when failure might occur, but it does not tell us how to deal with the potential failure economically. Essentially, if you have a wide dispersion of probability of failure in time, you have a greater likelihood of investing too early and suffering the cost of capital over a longer period. Such early investment in replacement is only viable where the cost of failure is large in comparison to the cost of preventive replacement.

To drive replacement efficiency you have essentially two strategies; you must manage or reduce the consequences of failure through risk management (fire prevention, spares management, design redundancy etc), or reduce the dispersion of the failure probability. It is to this second strategy that we address the remainder of this paper.

3 Condition Assessment

In general, component failure occurs as the result of intrinsic and/or extrinsic forces acting on the deteriorated component. Failure of "as-new" components can occur through the action of, for example, vandalism, fire, and inadequate design, but from the perspective of efficient replacement timing we do not concern ourselves with these failure modes. Deterioration of the component results from a combination of design, operation, environment, and maintenance. The variability of these parameters results in different rates of deterioration, even amongst identical components, and shows as failures being spread over time. While we may calculate failure probability as a function of time, time itself is usually not a deteriorating agent of infrastructure assets.[3] When we consider failure probability just against time, or more properly age, we are incorporating the combined variability of design, operation, environment, and maintenance, the result of which is invariably a wide dispersion of the failure distribution and the general inability to economically justify preventive replacement at a reasonable level of risk. Despite this, it is common to see failure probabilities only determined against component age and it is equally common to find asset managers disillusioned with statistical approaches to asset management.

When we make condition assessments on components, we cut straight to the effect of any deterioration on that component. If we can then define a relationship between our measurement of condition and the probability of failure of the component, this derived distribution against condition will be significantly less dispersed than the equivalent failure probability against age and our economic test will be achieved at a lower risk.

The conclusion that we have arrived at is largely common sense; that by measuring the degree of deterioration of components, for example, corrosion, rot, loss

[1] Our model also avoids the complication of valuing the optionality of the replacement decision as we assume the replacement timing is arranged to meet a fixed level of risk.

[2] For example, determining an appropriate threshold risk for preventive replacement.

[3] The most common exception to this deterioration of material strength due to chemical action at ambient temperature that manifests as deterioration against age alone.

of section, vibration, cracking, partial discharge etc, we gain better insight to their hazard of failure than by looking at their age alone. Most companies already do this and, through risk classification, assign replacement priority to the most deteriorated components. However, by understanding this relationship within our conceptual framework, we reveal it to quantifiable analysis and, by extension, can consider other asset management problems such as the valuation of asset information. The key to these benefits, however, is the translation of condition measurement to failure hazard, which we put forward as the core problem to solve in determining efficient replacement expenditure.

4 Case I - Large Generator Failure Hazard

To illustrate a method of translating condition to failure hazard, we consider a fleet of large generators in the range 20 to 40 MW each turned by water-wheel turbines. The generators are assessed by a number of tests including visual inspections and given weighted condition scores on their main component parts generally subject to deterioration, these being the stator winding, stator core, and rotor winding. Condition assessments are made approximately yearly. Ideally, we would have a history of condition measurements and failures upon which to base our relationship of condition to hazard but this type of information is seldom, if ever, available in practice. Instead we must look to other means to approximate the relationships.

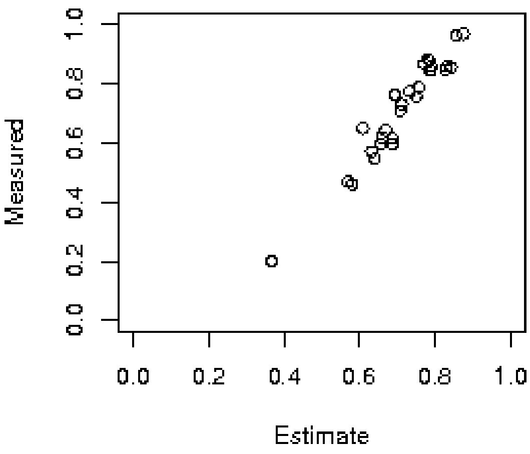
For this fleet of assets, the translation of condition to hazard is undertaken in two parts. Firstly, the condition is derived as a function of the generator design, operation, and age so condition may be projected over time. Secondly, the condition to hazard relationship is determined based on known survival trends in the fleet combined with published survival trends for similar assets.

The condition projection is based on regression analysis that compares the condition of the generators at their various ages combined with factors that influence the rate of deterioration (operating temperature, bar force, utilisation etc). Because this fleet of generators are all of similar design,[4] the predominant predicting factor is the utilisation. This analysis is possible because the generators have a spread of conditions and ages that enables a relationship to be estimated. The spread of measured condition against estimated condition for the generators with asphalt stator windings is shown in figure 3.[5]

[4]The fleet has a mix of asphalt and epoxy stator windings but these are treated as separate populations

[5]The reader may note the fit line pivots about the 0.7 condition point indicating there is an unresolved bias in the model. It is hoped the model will be improved and this bias removed in time as more condition points become available at lower condition scores.

Figure 3: Asphalt Stator Winding Condition Model Fit



Examples of condition projection curves and historic condition measurement points are provided in the chart of figure 4. As an additional benefit of the approach, measurements off the condition projection line identify generators behaving inconsistently from their design and operation and so provide better outlier identification and direct further investigations.

The condition to hazard relationship is determined by setting a target survival curve for the fleet as a whole, based on a combination of known survival and published curves, then, using non-linear numerical methods, we find a condition to hazard relationship that matches the condition projections to the target survival. A number of assumptions are involved,[6] but the key idea is to start with individual condition projections for each item plus an expectation of how the overall population of items will behave in time, and then reverse-engineer the relationship between condition and hazard that joins these two expectations.

For our fleet of generators, the condition to hazard relationship takes the form $H = exp(a + bC)$ where H is the hazard (per year), C is the condition and a and b are co-efficients discovered through the process discussed above. The hazards developed in this way give the asset owner a realistic estimate of the true failure probabilities posed by this fleet of generators that is in concert with the observed condition of each component. This information serves to forecast and prioritise replacement expenditure and informs wider asset management issues such as spares management and resource planning.

[6]Key assumptions are that the range of conditions and condition projections are representative of the population being described by the survival curve, that there is a single relationship between condition and hazard applicable to all components of the population, and that past behavior will be representative of future behavior.

Figure 4: Example Condition Forecast Curves vs Age for 3 Stator Windings

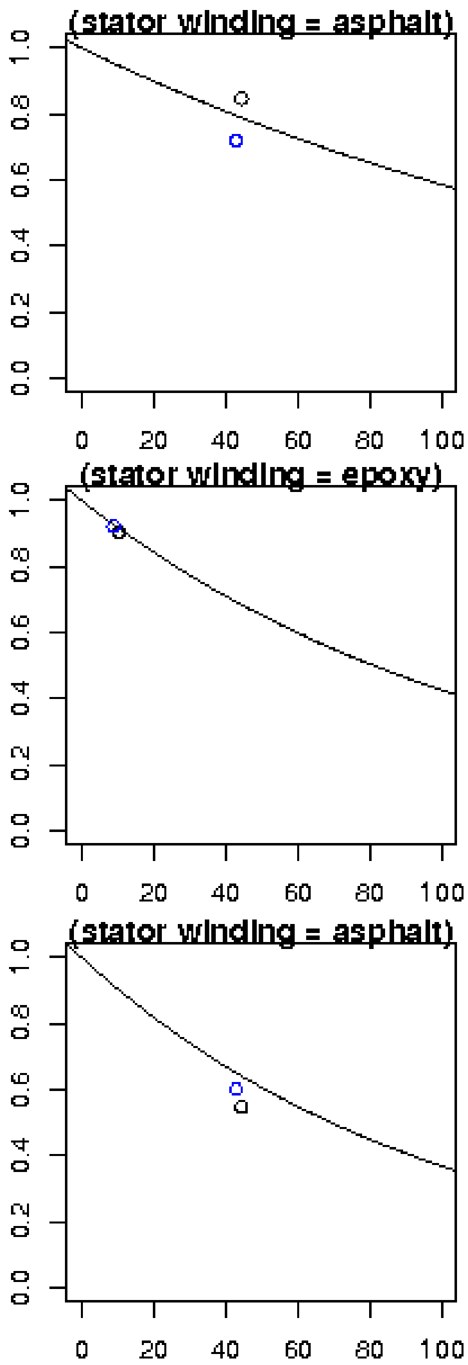
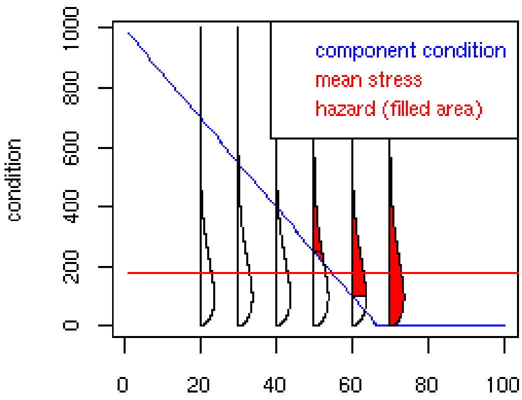


Figure 5: Pole Condition and Extrinsic Stress vs Age



5 Case II - Value of Better Information

In this second case study we consider the value of improving condition assessment information by examining the case for implementing a new condition assessment test on wooden power poles.

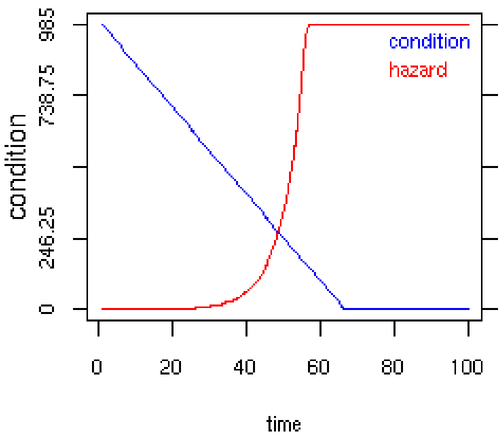
The physical failure of a power pole is a public safety hazard. Legislation requires that poles be regularly inspected and replaced when they are considered to no longer have the design strength required of them. The design strength is set such that the pole will be able to withstand a set of extrinsic forces that are likely to occur only rarely in practice, e.g. a combined wind and ice loading on the supported conductors. A safety factor is then applied above the design strength to account uncertainty in the pole material and allow for deterioration of the pole over time.

Poles are physically inspected and the remaining strength of the pole inferred. The assessment test being employed is a “hammer test” under which the pole is sounded and if found soft is further investigated by drilling. The method is fraught and relies on consistent interpretations by the inspectors. As such, a conservative approach is applied resulting in a portion of serviceable poles being condemned. The problem to be addressed is to quantify the extend that loss of useful life might be reduced by adopting a better, but potentially more expensive, condition assessment test.

We start by expanding our conceptual framework on the relationship between condition and the requirements on the condition (stress in this example), which is illustrated in figure 6. This figure plots condition on the y-axis against time on the x-axis. In this example, condition decreases linearly with time and is expressed as the ability to resist stress. Overlaid on the plot is the distribution of extrinsic stresses imposed by the environment.

When the pole is new, the condition sits well above the distribution of external stress, but as it ages the

Figure 6: Pole Condition and Hazard

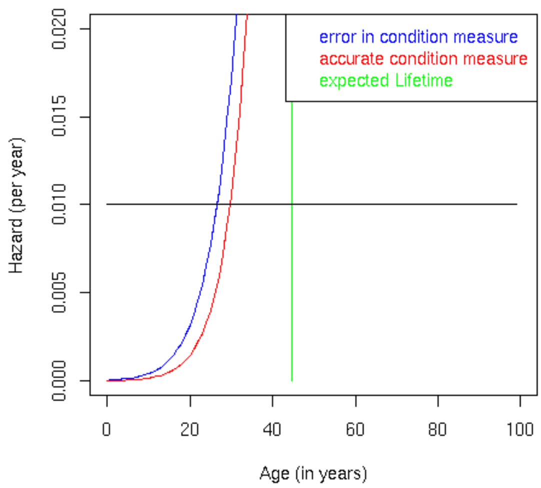


strength (viz condition) decreases and it becomes exposed to an increasing proportion of the distribution of external stress against which it will fail, as illustrated by the red shaded areas in the figure. These shaded areas represent the probability of physical failure with changing condition from which we can derive the hazard curve as illustrated in figure 6, that shows on separate axes the change in condition with time and the failure hazard with time.

Uncertainty or error in knowledge of the true condition of the pole may be represented by a vertical band about the condition line in figure 5. If we select a low probability of physical failure (at the design stress), this sets the condition at which we should replace the pole. However, if we wish to maintain the same risk but account the error in what the true condition is, we have to shift back along the elevated "error" condition line in time until we mark off the same area. This shift in time is the effective loss of serviceable life of the pole because we do not know the true condition but wish to maintain the same level of risk. This is represented in figure 7 that shows the hazard curve assuming accurate knowledge of the condition and the hazard with a 10% error in knowledge of the true condition. At 1% risk (the horizontal line) the time shift is approximately 4 years in this example.

In order to quantify the loss of servicable life, we need to know the characteristic of the condition deterioration and the characteristic of the environmental stress. From published papers we understand that wood pole strength generally deteriorates linearly with pole age [1] and because the key environmental stressor for pole lines is the square of the wind gust speed, we may estimate the environmental stress distributional shape based on wind gust data for the areas of interest to us. Using this information, we derive tables of the condition measurement error and the associated loss of serviceable life, to which we can ascribe monetary value, for different levels of accepted risk. This gives us the criteria needed to evaluate the benefits of improved condition measurement

Figure 7: Example Time Shift with 10% Error in Condition Measurement



tests against the cost of implementing those tests.

6 Conclusion

We have outlined a conceptual framework to show that understanding component failure hazard through component condition measurement is the core problem to solve to implement efficient asset replacement. This concept is expanded in two case studies that demonstrate practical techniques in applying this conceptual framework to resolve real-world asset management problems.

7 Additional Remarks

The following additional remarks expand on the general issue of replacement.

1. The method of determining hazard described in the first case study relies on making an estimate of the population survival. Caution needs to be applied when using published or even in-house data in this area as it is common to find survival statistics based on replacement rather than failure, or a mix of the two. When recording asset history, it is important that the reason for replacement is noted.

2. Establishing a relationship between condition and failure hazard is the core problem to solve but it is not an end in itself. Failure hazard only becomes useful when combined with encompassing asset models that consider the wider issues of spares management, co-incident replacement with growth, maintenance, risk management etc.

3. Replacement should not be considered from the perspective of capex alone. It is better to consider the problem from the perspective of finding a set of actions (maintenance and/or capital) that minimise the present value of future costs including risk costs.

4. Valuing consequences is, in general, a less difficult problem than evaluating failure probability. A powerful method that we often employ is to solve for the level of reliability required of a component to avoid preventive replacement. It is often easier to say .."I do not know what the reliability is but I know it has to be less (or more) than that".

5. Dispersion in failure times effectively smooths replacement expenditures over time where there are large numbers of individual items of varying ages. When reviewing replacement expenditures in these circumstances we would expect to see smooth transitions in replacement expenditure between years. Where this is not the case, the expenditure commetary should either describe a change in unit costs (or accounting policy) or a change in risk policy.

References

[1] Renforth LA. Pole testing ensures high reliability and long life. Transmission & Distribution World, December 2002, pg 44

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