Asset Replacement Planning: One Size Does Not Fit All

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Electricity Networks Asset Management Conference - November 2007

Abstract

Applying a single defined life to all assets of an asset class in order to forecast future replacements does not work in almost every case, yet remains the mainstay of electricity distribution industry practice. Better asset replacement planning increases business valuation and lowers risk, but remains elusive because no single methodology is applicable to all asset types.

This paper discusses the deficiency of methodologies using 'defined lives' for all asset classes and presents two improved methods exemplified in two case studies of asset replacement planning where the methodologies better match the specifics of the asset class. Both case studies reveal significant value to the asset owner by identifying appropriate means to reduce future costs.

1 Introduction

Capital planning within the electricity distribution industry is generally classified as either *growth* or *renewal*. In the terminology used here, *growth* covers both new acquisitions and assets replaced due to insufficient rating; *renewal* covers assets replaced due to insufficient performance at or within their given rating. This paper deals only with capital planning for *renewal*.

The mainstay of industry practice for renewal planning is the application of a defined life and per unit replacement cost to an asset class. Future renewal capital is calculated by applying the defined life and cost against the age profile of the associated asset class. This is, in essence, an extension of the ODV[1] network valuation methodology as it is common to use the ODV asset class life as the defined life.

The ways of applying a single defined life to an asset class, including condition-based age 'shifting', is discussed with reference to a wood pole replacement forecasting example and the deficiencies of such approaches are highlighted.

The issue of replacement planning is then framed in the context of solving two core problems; (1) identifying appropriate context for grouping assets, and (2) forecasting life cycle costs. To demonstrate improved methodology, two case studies in asset replacement planning are presented:

1. A small number of high value components, in this case large transformers, where the assets are treated individually and where the replacement planning issues lie in control of risk and the economics of life extension.
2. A large population of low value components, in this case tariff meters, where individual assessments are not feasible and where the replacement planning issues lie in identifying sub-classes and modelling life cycle costs.

2 Using Simple Defined Life

The application of a defined life to an asset class is considered in two methodologies; simple profile mirror, and condition-based age shifting. A third method, historic loss matching, is also discussed for comparison. Note that the replacement ages and context given here are illustrative only.

[1] Optimised Deprival Value (ODV) is the common method of valuation of distribution networks under regulatory control.

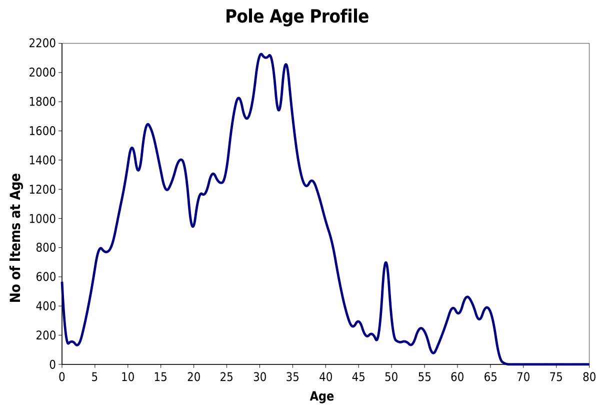

Figure 1: HV pole age profile

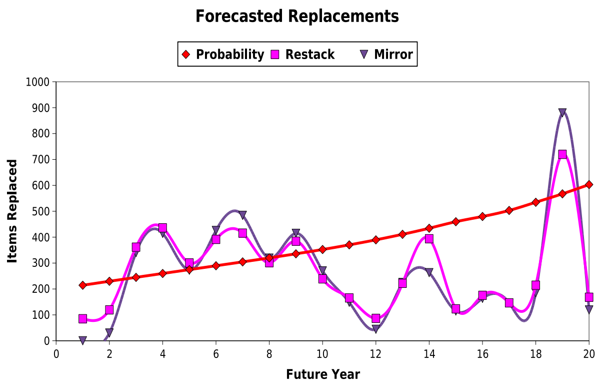

Figure 2: Replacement forecast comparisons

2.1 Simple Profile Mirror

This method applies a defined replacement age such that every item is assumed to be replaced when it attains that age. The effect is to mirror the asset class age profile about the replacement age.

Figure 1 illustrates an age profile for wooden poles and figure 2 demonstrates replacement numbers for the three forecasting methods for this asset class to a 20 year horizon. The simple profile mirror methodology is given by the 'mirror' line assuming a defined replacement age at 67 years. The replacement numbers show as a mirror image of the age profile over the forecast period.

The deficiencies of such a simple methodology are clear as it is implausible to hold that all the items of an asset class will fail at the same age. The inherent implication of a direct correspondence between condition and age is also unfounded. The only practical sense where replacement may follow such a model is where asset performance is tied to some business context e.g. an asset always last more that 'y' years but regulatory compliance costs (eg safety testing after 'y' years of age) are uneconomic and force replacement.

2.2 Profile Re-stacked on Condition

This method is an extension of the simple profile mirror and is used by regulators in some jurisdictions in Australia and the United Kingdom. In this method the item ages are 'adjusted' dependent on the percentage of items assessed as being in either better or worse condition than their age would imply. If a population sample is inspected and assessed as having 15% of items in worse condition than the item ages would suggest, then 15% of the items in each age group have their 'condition age' increased by the maintenance interval for that asset class (say 5 years). The inverse is undertaken for the percentage assessed as being in better condition than their age would imply. Any items in the revised 'condition age' profile with ages still exceeding the given defined life are classified as 'risk managed' and assigned ages that spread their number over the maintenance interval immediately before the defined life.

The revised age profile is then reflected about the defined life to obtain the replacement forecast. For the pole profile, the revised replacement forecast under this method is given by the 'restack' curve in figure 2 where we assume 5% in good condition, 20% in bad condition, and the maintenance interval is 5 years.

While this method is generally better than our simple profile mirror, it still suffers a number of deficiencies. These include:

1. The replacement forecast shows significant year-to-year variation which is generally not observed in practice due to the large variability in failure age that is characteristic of distribution network

components.

2. There is (generally) no evidential foundation for the defined life used, nor evidential reason to assume that the asset class maintenance interval is a proxy for the dispersion in failure age.

3. Changing 'effective age' based on condition implies a single relationship between condition and age for which there is no evidentual reason.

2.3 Probabilistic

This method determines a hazard function[2] that describes the probability of an item failing at a given age. The determination of failure hazard is described in a number of texts [1] and is used within the second case study discussed later. The 'probability' curve on figure 2 shows the replacement forecast for our poles example where a hazard curve has been derived from pole failure data. Having derived a hazard curve based on historic replacements, future replacements are forecast by applying the hazard to the age profile, year-by-year, into the future.

The advantage of this approach is that it yields smoother forecast curves that may be verified by comparison to the current failure rate averaged over the last 2 to 3 years. Another key advantage is that the derived failure hazard yields additional information about the dispersion in failure age that may be used to determine the most cost effective method for managing the associated costs from item failures.

Unfortunately, within the distribution industry there is usually insufficient data to properly determine the hazard relationship to asset age. The most common weakness encountered is data systems that fail to record, or are able to reconstruct, the context of failures, i.e. in year 'y', 'r' wooden poles of age 'a' were replaced due to condition where at the beginning of year 'y' there were 'p', age 'a', wooden poles.

There is a method to approximate the hazard function based on the difference between the current age profile and the built age profile. Figure 3 shows an age profile for a network's distribution transformers

[2]A hazard is a conditional probability; it is the probability of failure in the time interval 'x+1' given it is alive at time 'x'.

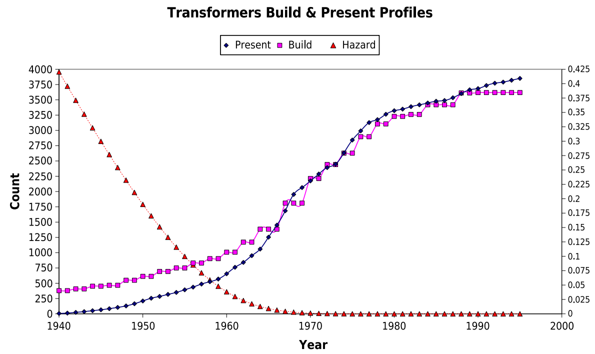

Figure 3: Transformer build and present profiles

together with the built age profile derived from Electrical Supply Authority (ESA) returns. Note that the profiles are set-out based on install year rather than age. The difference between the two curves represents the transformers that are no longer installed in the network. Figure 3 also shows a hazard curve fitted such that when it is applied to the build profile, it yields the current profile. The main disadvantage of this method is the inability to distinguish between replacements made for reasons of growth and those for renewal. As such, it is generally only applicable to overall budget forecasting or for cost approximations in due diligence investigations.

2.4 Existing Methods Deficient

Existing renewal planning methods are deficient. Simple replacement planning based on defined lives for asset classes are almost always inappropriate for replacement planning purposes as they over-simplify the situation and lack the overlay of business context in which decisions must be make. Extention to incorporate concepts of condition will fail if the grouping of assets is inappropriate. In all cases, the nature of how failures occur in time must be understood as a prerequsite to understanding the value of renewal planning.

3 Improvement of Methods

We focus on two core, interrelated issues, for achieving better renewal planning.

1. Determining appropriate groupings of assets.
2. Forecasting life cycle cost as a means of achieving economic efficiency in renewal planning.

3.1 Grouping Assets

At a detailed level, every asset, from a power transformer to a pole crossarm, may be considered to have unique circumstance in design, installation, operation, and failure consequence. It is, however, only practical to consider assets in their *individual context* when they are of high capital value.

Other, less valuable assets, need to be grouped, primarily in accordance with common physical performance, but may also consider:

- Ability to identify the asset group in the field.
- Unique business context (failure consequence, safety issues etc).
- Compliance issues.

3.2 Life Cycle Cost Forecasting

A renewal plan must be able to demonstrate economic efficiency for the benefit of shareholders or to a regulator. Interventions over the life of an asset, including renewal, must be considered from the perspective of investments that will deliver some future return. We therefore look to forecast life cycle costs over some time period and amortise these costs as the basis of our cost minimisation goal.

Because we are concerned with how costs disperse in time, we must also be concerned with how failures, of individual assets or in a population of indistinguishable assets, disperse in time. Just knowing the average life of our asset class is not enough to make judgements about the economic efficiency of our renewal plan.

3.3 Case Studies Demonstrating Improved Methodology

Two case studies reveal the issues discussed above. The first concerns the methods for individual asset context. Here we consider management of a small population of large transformers and show the planning issues lie in appropriate timing of maintenance for life extension as well as spares management. In this case, transformer replacement is simply one of many possible interventions to manage future risk at minimum investment cost.

The second case study considers the issues of appropriate grouping by identifying performance of sub-populations. Our case study concerns replacement planning for a large number of domestic tariff meters. The case shows the importance of recognising different failure characteristics of sub-populations in combination with lost revenue from meter failure, on the appropriate timing of planned replacement.

4 Case 1 - Transformer Replacement Planning

This case study considers appropriate timing for mid-life refurbishment on a large transformer. It illustrates key aspects of capital planning including separation of the physical and business context, inclusion of risk management, and focus on net present value as an over-arching goal.

We consider the case of a generator unit transformer at a multi-unit power station. We seek a set of interventions, that include refurbishment, replacement, and purchase of spares, to manage the risk of lost generation and failure damage, and minimise the life cycle cost amortised over a given planning horizon. Note that:

- We are not seeking a replacement plan as such. We are seeking a set of interventions, be they capital or maintenance, that achieve some goal.
- The interventions do not have to be physical. They could include actions that act only within the business context, such as risk mitigation

through hedge contracts or contracts of insurance.

- The interventions change future performance or behavior so must be considered from the perspective of an investment. The goal is therefore measured as an amortisation of costs over our planning horizon.

The following describes a specific modeling methodology used by the authors. We do not imply it is the only method, but one that we have found to be useful in undertaking these types of problems.

4.1 Physical Model and Method

Each transormer asset is considered within a wider grouping of other transformers (and potentially other plant) where inter-relationships may exist, such as the sharing of spares.

Each transformer is modeled as an asset comprising a collection of components that may themselves be comprised of components. Each component may have a number of failure modes. Figure 4 illustrates our transformer asset consisting of bushings, tap changer, core-winding and coolers.

The failure modes are each described by hazard functions that relates the likelihood of the failure occurring within some time step (usually 1 month) to the age of the component. In the simple case of a bushing, the effective age is just the actual age multiplied by the utilisation. In the more complex case of the core-winding, we separately model the winding insulation strength, in degrees of polymerization (DP), then calculate a forward-going hazard function with time that chains a standard estimation of failure rate with DP strength, to our specific DP strength with time projection.

Each failure mode initiates a *consequence tree.* Figure 5 illustrates an example consequence tree for failure of the core-winding component. The consequence tree describes the set of possible outcomes of the failure mode dependent on a number of risk controls. Risk controls may include such things as the action of automatic electrical protection and the automatic or manual application of fire suppression. The effectiveness of the risk controls are expressed as a probability

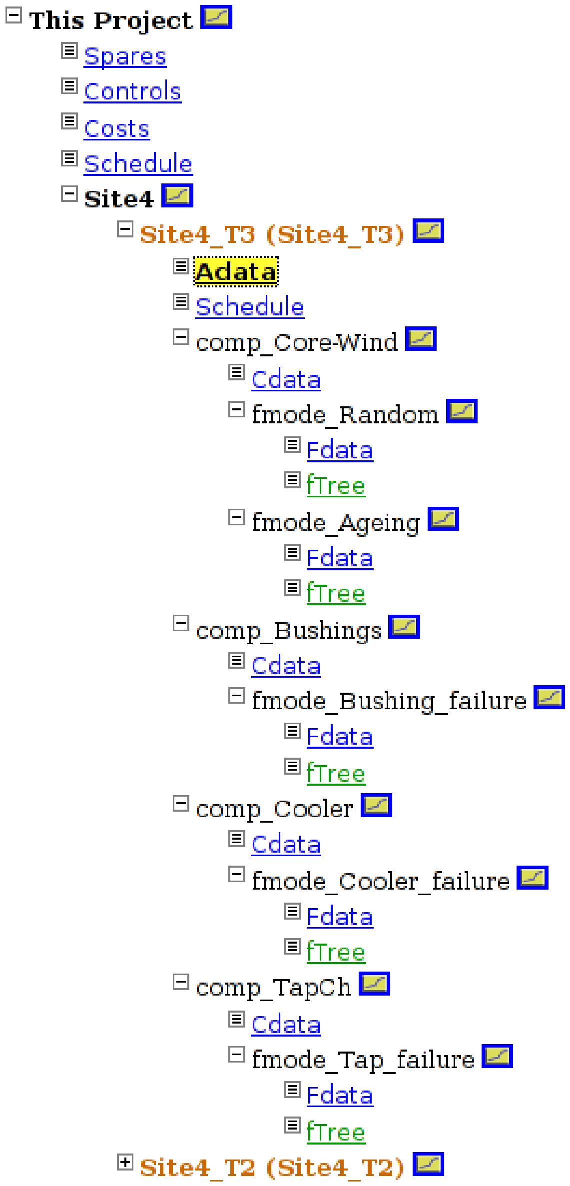

Figure 4: Transformer failure modes structure

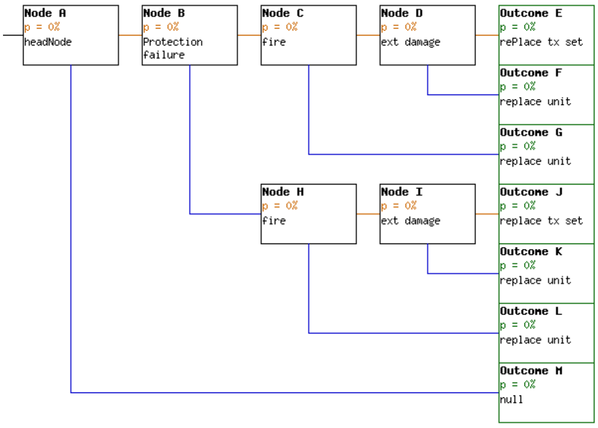

Figure 5: Core-winding failure consequence tree

of passing out the true or false node of the branch. At the outcome *leaves* of the consequence tree, the state of the system is interpreted and acted on by one or more maintenance and replacement policies. For example, failure of a bushing with no fire will result in replacement of just the bushing unless the condition of the core-winding is poor, which may then initiate replacement of the whole transformer.

Key advantages of this approach are:

- The physical and business contexts are decoupled.
- The elements of the problem are suitably partitioned.
- A standard asset template may be developed and then 'cloned'
- The value of risk controls may be examined and quantified
- The effect of different maintenance and replacement policies, including spares holdings, may be tested.

4.2 Condition and Risk

The translation of component condition to failure risk is the most difficult part of the problem and a significant source of error in the model. Valid statistics on failure rate with age or failure rate with condition are not available because:

- Large power assets are replaced due to perceived risk or capacity issues; few are run-to-failure replacements because owners wish to avoid failure consequences. Quality data sets identifying the true life of assets and components are generally not available.
- Changes in transformer insulation and construction methods over time, together with differing operational and maintenance histories and operating environments, make like-for-like comparison between transformers difficult.

The method used by the author to best approximate the risk with condition is a *backwards-forwards* approach. The risk with condition function is back calculated by solving for a risk function that produces a target survival characteristic on the owner's transformer population, given forecasts of the condition with age for each transformer. The target survival is based, in part, on the known failure history of the owner's transformers, and in part on international experience with similar transformers. The transformer's condition with age projections are based on a mix of historic recordings of condition when available, engineering expertise, and regression models. The present risk on each transformer is forward calculated using the condition to risk function and the risk ranking and overall failure rate assessed to see how well they match the current observation of overall failure rate and the risk ranking expectation by the owner's engineers. One or more iterations of the process may be required.

4.3 Transformer Life Extension

In the transformer case we consider the effect of a mid-life refurbishment, being oil reclamation and winding dry-out (for a free-breathing transformer), on the condition of the transformer over time, where DP is our proxy for winding condition. The degradation of DP with transformer age is based on a formula [2] describing the effect of time and increasing acidification of the insulating oil. The effect of oil

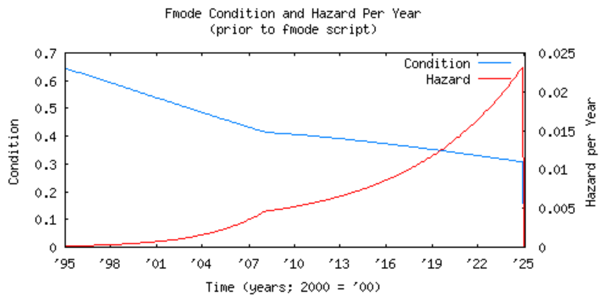

Figure 6: Effect of transformer refurbishment

reclamation and winding dry-out is to regress the DP deterioration rate thereby extending the transformer life. This is illustrated in figure 6 where the (top) blue line is the DP condition and the (lower) red line is the associated failure hazard.

4.4 Availability of Spare Transformer

The consequence of a transformer failure is very dependent on the availability and installation time of a spare unit. In our case a transportable spare is scheduled to be purchased. The availability of the spare must be considered within the wider context of the group of transformer assets serviced by this spare. For any particular transformer failure there is only a probability of the spare being available and this probability will vary in time and circumstance. In our methodology, spares holdings, spares ordering and spares delivery are specifically modeled.

4.5 Transformer Case Outcomes

Table 1 sets out the net present costs, inclusive of refurbishment, failure damage costs and business interruption costs (lost revenue), over a time horizon of 2007 to 2025, on one transformer under an example set of scenarios being:

- Replacement when DP condition falls below 200 (0.2 pu)
- Refurbish in 2008 at opex cost of $100k

Net Present Cost	No Common Spare	Common Spare in 2010
No Refurbishment	$469k	$374
Refurbish in 2008	$212k	$175k

Table 1: Transformer case example outcomes

- Common (transportable) spare available from 2010 with 20 day delivery

Figure 7 shows the risk cost over the period 1995 to 2025 with transformer refurbishment in 2008 and a common transformer spare available from 2010.

As shown, the case for refurbishment is leveraged on the future purchase of the common (mobile) spare transformer. This demonstrates how capital planning is dependant on both the physical deterioration of the asset and the business context of the asset (in this case the failure consequence costs).

Extended analysis showed the lowest life cycle cost was with locating a mobile spare at this site reducing installation time to 3 days, no refurbishment, and a run to failure strategy, however this is very dependant on the particular business circumstance and the risk controls applied.

4.6 Transformer Case Study Conclusions

Capital planning for large asset classes must explicitly consider both their physical and business context. Understanding and quantifying the interactions between the physical and business contexts, and how these develop over time, is a complex undertaking but yields value to the asset owner through lower life cycle cost and ability to demonstrate economic efficiency to share holders and/or to a regulator. Key ideas include:

- Physical context should be considered from the perspective of failure modes.
- Failure consequence is mitigated through application of both risk controls, spares management,

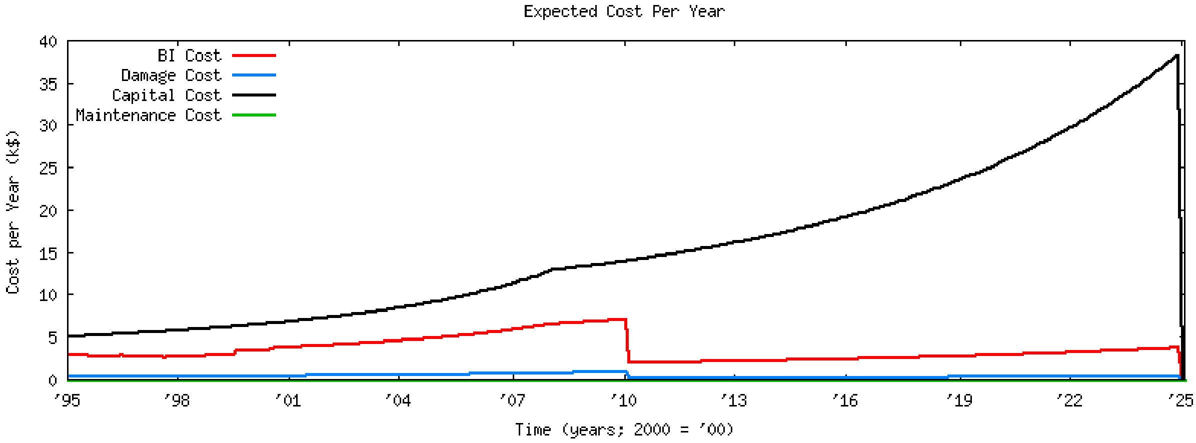

Figure 7: Transformer risk cost trend

and maintenance and replacement policy.

- Appropriate maintenance and replacement policy and plans require the developing and testing of different scenarios.
- Life cycle cost goals should be represented as amortised sums of future costs including risk based costs.
- An understanding of the progression of asset condition and the translation of condition to failure risk is needed.
- It is better to consider relative changes in life cycle cost when considering different maintenance and replacement policy scenarios due to the inherrent difficulties in quantifying the true value of risk.

5 Case 2 - Replacement Planning of Domestic Tariff Meters

This case study considers the replacement planning issues of a large number of installed meters on a 'business as usual' basis to establish the most efficient means of managing the meters under the base case assumptions. Replacement driven by business advantage from new metering technology may be considered subsequently relative to the base case but is not considered here.

In this case study the meters are grouped under a three-level hierarchy:

- At the top level is the category/class (for example whole current mechanical class 2)
- Under each category/class are a set of generic models. These are essentially groupings of manufacturer (make) and model with (assumed) indistinguishable performance. They often, although not necessarily, are made up of the same manufacturer's near similar models.
- The make and model is the lowest level grouping.

While this case study is based on real field data, the meter identifying names used here are fictional.

This case study relates to a generic model 'T1' which is part of the category/class 'whole current mechanical class 2'. This generic model identifies 15,600 meters and comprises 52% 'Fujip T1' and 48% 'Fujip T1-square' as the (fictional) make-models.

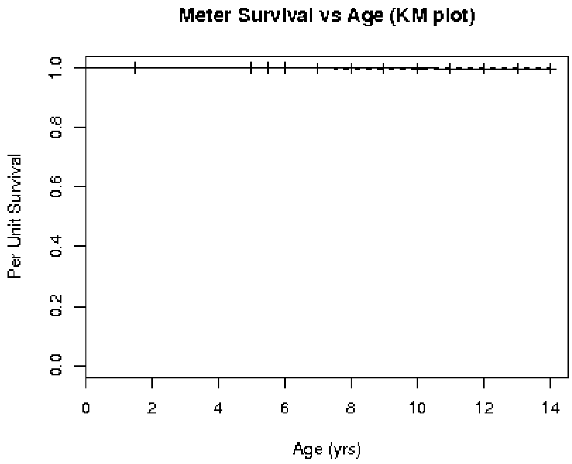

Figure 8: Survival of generic 'T1' meters

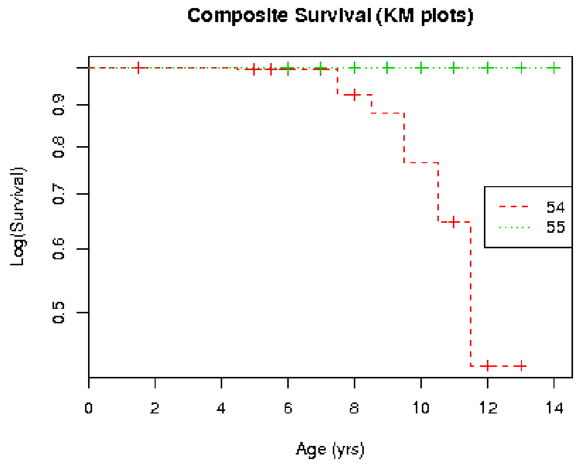

Figure 9: Survival by make-model
[54 = Fujip T1; 55 = Fujip T1-square]

5.1 Homogeneous Assumption on Generic Model

Performance analysis on the generic model 'T1' revealed no appreciable difference in accuracy performance (based on sampling data) between the comprising make-models and there were no issues of concern regarding accuracy compliance requirements over the useful life, taken here as 40 years. Additionally, the present failure rate of this generic model was only 0.25% (sum total failures to installed meters) and the survival analysis[3], provided in figure 8 showed no reason for concern. Based on this assessment, the combined (all meters) cost projections for capital and opex expenditure over a 25 year forecast had a net present cost of $3.14M.

5.2 Generic Model is Not Homogeneous

Breaking down the survival analysis on a make-model basis, as illustrated in figure 9 showed the 'T1' generic model grouping was not homogeneous and the 'Fujip T1' meter (id 54) was showing a significantly different failure characteristic with a much earlier expectation of failure. This is not revealed in figure 8 because the differences in distribution of ages between the two make-models masks the true survival characteristics of each.

A distribution fitting process is used to characterise the failure observations for 'Fujip T1' meter, which fitted an off-set Weibull distribution. The fitted distribution is used to forecast future failure behavior. This projects a sharp increase in failures at about 19 years of age for the 'Fujip T1' meter that alters the forecast asset costs assuming these meters are not proactively replaced to avoid these future failures. The most significant change is a large opex cost increase around year 2012, due to revenue losses from meter failures. Capital costs are not changed significantly. Under this forecast the present value of the future costs over all meters has increased by $840k to $4.61M on a 25 year forecast.

[3]Survival analysis uses the failure histories to determine the expected proportion of meters to be in-service (surviving) with increasing meter age. The analysis undertaken here uses the Kaplan-Meier (KM) estimator method.

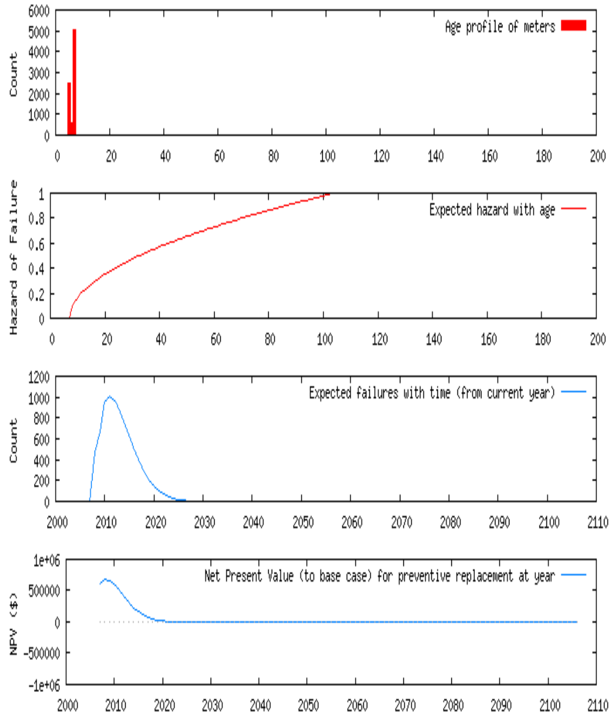

Figure 10: Meter Replacement Optimisation: Age Histogram; Failure Hazard with Age; Failure Numbers with Run-to-Failure; Relative NPV for Preventive Replacement

5.3 Optimal Replacement Planning

Having characterised the likely future performance of the 'Fujip T1' meter population, this may be used to resolve the optimum replacement time to minimise the combination of cost of replacement capital and opex cost due to revenue loss and higher replacement cost per unit when replacement is unplanned. This is achievable because the failure distribution describes not only the characteristic life but also the dispersion of failure about the characteristic life. An example analysis for this case study is illustrated in figure 10 where the charts show in turn:

Histogram — The 'Fujip T1' present age distribution

Hazard — The anticipated failure probability (hazard) with age

Failures — The future distribution of failure numbers given no planned action

PV — The present value of future costs given planned replacement is undertaken at that year. The time at which this curve maximises indicates the optimum time for planned replacement of the in-service meters of this type.

The analysis indicates that planned replacement should be undertaken in 2008 and will result in a saving of $675k compared to a run-to-failure or design life strategy. Note that in this analysis a 'same technology' replacement has been assumed. Replacement with a new technology may be examined by inclusion of a net benefit per meter in the analysis input. Additional benefits bring forward the optimal replacement time.

5.4 Revised Cost Forecast

Setting planned replacement for the 'Fujip T1' meters at year 2008 alters the total asset cost profile by increasing capital spend in year 2008 but significantly reduces the future opex liability reducing the present value of future costs to $3.94M over the 25 year forecast. The capital and opex cost forecasts for the three stage progression of the original plan, forecast after identifying the early failure potential, and revised plan with preventive replacement, are set out in figure 11.

5.5 Meters Case Study Conclusions

This case study reveals that where sub-populations within a larger grouping of similar assets have different failure behaviors these differences may be material to establishing an accurate renewal forecast. Establishing the degree to which the items within an asset class are homogeneous is an important step in developing the renewal plan.

It is necessary to determine both the characteristic life and the failure dispersion of lives, together with knowing the business context of asset failures,

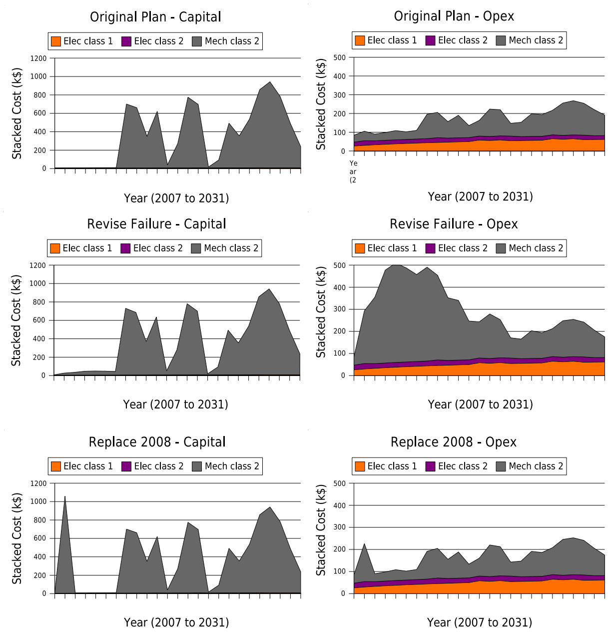

Figure 11: Capital and Opex forecast progression

to enable an assessment of both the expected future behavior and an appropriate response to minimise future costs, inclusive of cost of capital.

6 Conclusion

The two case studies presented show vastly different approaches are needed for replacement planning between different asset classes. The key issue is understanding the physical failure mechanisms and the business context in which those failures occur.

References

[1] Nelson W, Applied Life Data Analysis, John Wiley & Sons, 1982, ISBN 0-471-09458-7

[2] Faville D, A Transformer Renewal Strategy, Electricity Engineers Association Annual Conference, June 2002