Asset Risk Model Framework (REPEX)

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Author:

Mark Alexander
Digitally signed by Mark Alexander
DN: cn=Mark Alexander, c=AU, o=Endeavour Energy, ou=Asset Planning and Performance, email=mark.alexander@endeavourenergy.com.au
Date: 2022.11.14 11:37:06 +11'00'

Mark Alexander
Lead Engineer Asset Investment

Endorsed by:

David Mate
Asset Performance Manager

Approved by:

Digitally signed by Peter Langdon
DN: cn=Peter Langdon, c=AU, o=Endeavour Energy, ou=Asset Planning and Performance, email=peter.langdon@endeavourenergy.com.au
Date: 2022.11.14 17:49:13 +11'00'

Peter Langdon
Head of Asset Planning and Performance

1. Purpose and objective 5

2. Glossary 6

3. Overview 8

3.1 Introduction 8

3.2 Simplified repex risk cost approach 8

3.3 Asset failure 9

3.4 Probability of Failure (PoF) 11

3.5 Consequence of Failure (CoF) 12

3.6 Application of PoF and CoF to an asset 14

3.7 Annualised risk costs 16

3.8 Asset Retirement and proposed investment 16

4. Probability of Failure 19

4.1 PoF distribution function 19

4.3 Application of the Weibull distribution function 20

4.4 Weibull distribution parameter estimation methods 23

4.5 Derivation of parameters for an asset class and/or individual asset 25

4.6 PoF derivations 33

4.7 Application of the Common Network Asset Indices Methodology (CNAIM) 34

5. Consequence of Failure Model 35

5.1 CoF consequence categories 36

5.2 Likelihood of consequence (LoC) 36

5.3 Likelihood adjustments due to network configurations 37

6. Investment Selection 42

6.1 Investment Evaluation 42

6.2 Sensitivity Analysis 46

6.3 Reactive replacement 48

6.4 Credible options 49

7. References 51

Appendix 1 – Probability of Failure Functions 52

Appendix 2 – Non-repairable asset investment tool 53

Appendix 3 – Repairable asset investment tool 53

Appendix 4 – Weibull parameter estimation tool 53

1. Purpose and objective

The purpose of this document is to set out Endeavour Energy's Repex methodology for assessing condition-based risk for electricity transmission and distribution assets, for estimating risk cost and detailing how risk is used to make asset retirement, de-rating, and intervention decisions. This means that, where the Methodology is applied a common output shall be determined for a common set of input data.

The document aims to develop a common language for a number of risk concepts, including probability of failure and consequence of failure and gives an overview of how these models are developed and used in the context of asset management decision making.

The document also discusses how these concepts are used and compared against potential intervention options, how customer benefit is derived and how asset management recommendations based on a risk / benefit / cost trade-off are determined.

The processes outlined supports Australian Energy Regulators (AER) published guidelines *Industry practice application note – Asset Replacement Planning version January 2019* to meet National Energy Rules (NER) requirements to demonstrate the prudency and efficiency of network asset investment on asset retirement and de-rating decisions and in alignment with the National Electricity Objective (NEO) to achieve efficient long run service costs.

2. Glossary

Term	Definition
Australian Energy Regulator (AER)	The economic regulator
Assisted Failure	The failure of the asset is caused by an external factor which the asset was not designed to withstand. This type of failure is independent of the asset condition.
Censored	Censored data is any asset for which we do not know the exact failure event time. For this assessment, the functional failure event is unknown because the asset was retired before it was allowed to functionally fail.
Censored Left	Left censored data is data for assets that are known to have failed prior to the time the risk assessment was undertaken.
Censored Right	Right censored data is data for assets that have not yet failed. They are considered “still alive” as their failure time has not yet occurred, though it is expected to occur at some point in the future.
Cumulative Distribution Function (CDF)	The cumulative probability of a probability distribution at a given point along the function. When used for asset probability of failure (PoF) the cumulative probability the asset has failed by each age.
Consequence of Failure (CoF)	The risk expected to be incurred if the asset fails. The Consequence of failure is a product of the Likelihood of Consequence (LoC) x Cost of Consequence (CoC)
Cost of Consequence (CoC)	The cost of the average consequence for a risk category if an asset failure results in the consequence being realised.
Conditional Failure	The asset, by its condition, fails to satisfy safety or other performance metrics. It may still be functionally operable. E.g., a condemned pole.
Disproportionate factor (DF)	A multiplier to reflect the social willingness to pay for health and safety risk controls to emphasise the value society places on health and safety. Refer procedure GNV 1119 [1] for further detail and guidance for the use and calculation of the DF.
Financial risk	Direct financial costs that will be incurred following an asset failure. The cost of replacing or repairing the failed asset is included in financial risk.
Failure Mode, Effects & Criticality Analysis (FMECA)	Methodology to identify, assess and rank the risk associated with potential failure modes to identify and carry out corrective actions to address the most serious concern
Hazard Function	The instantaneous PoF according to a probability distribution. This is not used in the model as all calculations are over discrete time steps (years). However, taken on a year basis, is equivalent to PoF - Conditional
Health Index	The health index is a value between 1 (low health) and 10 (good health) on a continuous scale that represents the overall condition of an asset.

Hurdle rate method	A simple method for determining if an investment is economically viable. Also used to determine the optimum time for replacement investment in the life of an asset.
Linear asset	Assets that do not have discrete units, such as cables, conductors
Likelihood of Consequence (LoC)	The probability that a particular risk category will have a specific consequence following an asset failure
Non-Repairable	After failure the only feasible/economic network option is to replace the asset with a new equivalent asset. The new asset will be in good condition/health and have a lower PoF.
NPV method	A method for determining if an investment is economic using a discounted series of costs/benefits over the lifetime of the investment
Probability Density Function (PDF)	The relative PoF over a continuous scale. The PDF is the derivative of the CDF. The “modified PDF” is equivalent to the PoF -Relative
Probability of Failure (PoF)	The probability that an asset fails during a specified period
PoF Function	An equation that relates one or more characteristics of each individual asset to the probability of its failure.
PoF Function Form	The probability distribution or form of equation that is used to calculate PoF.
PoF Function Parameters	The values assigned to the parameters of the PoF Function form.
PoF – Relative	The probability an asset that exists today will fail in each future year. The sum of relative PoF over all future years is 100%. May also be termed “modified PDF”
PoF – Conditional	The probability an asset will fail in a particular year given it has survived until the start of that year. Used in the Hurdle Rate method
Post Tax Revenue Model (PTRM)	Determination on price and revenue constraints for each NSP issued by the AER for each Revenue Control Period
Repairable	After failure the asset is repaired and returned to service, with minimal improvement in asset condition and subsequently no reduction in PoF.
Risk category	A category of risk that is separately calculated within the model. Includes safety, financial, reliability, bushfire, legal/reg and environmental
Risk Cost	The asset Probability of Failure (PoF) x Cost of Failure (CoF)
Unassisted failure	A “functional failure” caused by the condition of the asset.
Weighted Average Cost of Capital (WACC)	The “real” “vanilla” values as published in the PTRM for the current regulatory control period for modelling investment issued by the AER.
Weibull Function	A probability distribution with three parameters often used for estimating PoF from asset condition data

3. Overview

3.1 Introduction

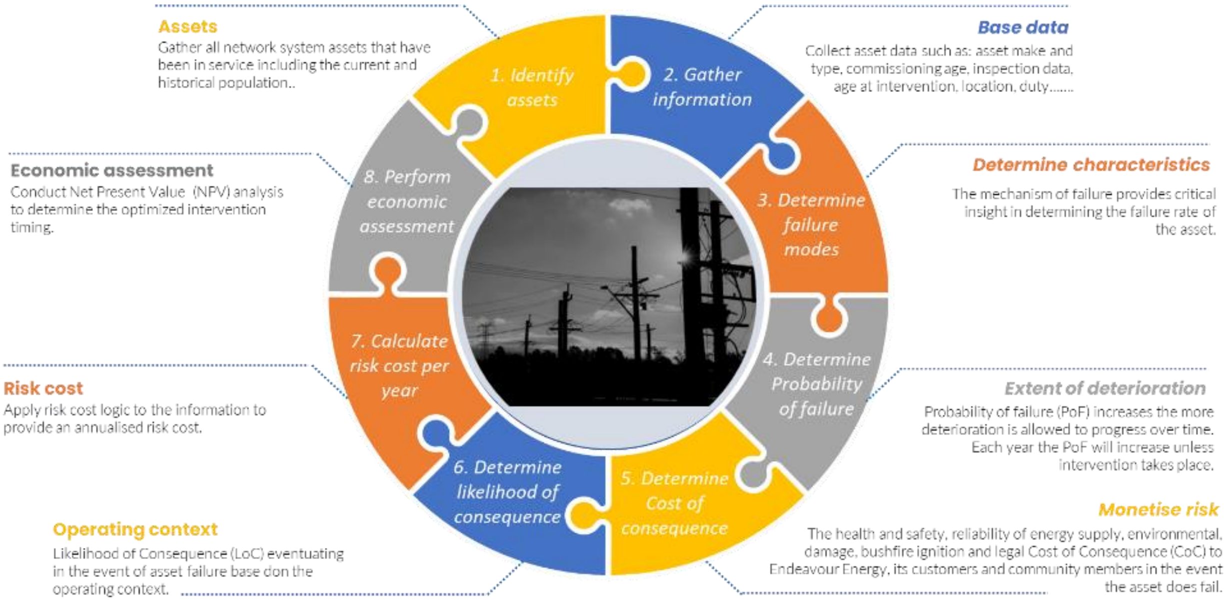
Endeavour Energy uses a number of approaches for the condition-based assessment of ageing assets ranging from simple inspection / condition-based maintenance regimes used for high volume low value assets such as distribution poles through to detailed technical analysis of key asset condition indicators used to assess high value assets such as power transformers.

In some cases, isolated individual assets become candidates for retirement due to a specific condition or performance issue. In other cases, assets of a particular manufacturer or model will emerge with type faults or simply due to age-based wear-out failure. Some assets may be found to carry a greater consequence than others if a functional failure was to occur in relation to the asset's location, energy supplied or vicinity to a populated area.

Where capital expenditure on renewal is proposed, the asset will have initially undergone an economic evaluation outlining risk cost and benefits of the proposal detailing how risk was used to make asset retirement, de-rating, and intervention decision.

The primary steps of the asset risk methodology framework are outlined in Figure 1 below.

Figure 1 - Asset risk cost modelling framework



This framework will ensure that the risks presented by the asset are quantified in consistent monetary terms to achieve consistent risk-based repex investment decisions for all network system assets.

The following document outlines the architecture for Endeavour Energy's asset risk model for repex based decisions.

3.2 Simplified repex risk cost approach

Asset failure is usually the greatest contributor for the majority of risk costs from an asset replacement planning perspective.

To assist in evaluating and understanding risk associated with the failure of an asset, failure events are reviewed and monetised by solving a risk cost equation. This approach is applied for all assets for replacement planning and supports the investment decision making process.

This simplified risk cost calculation can be shown in the equation:

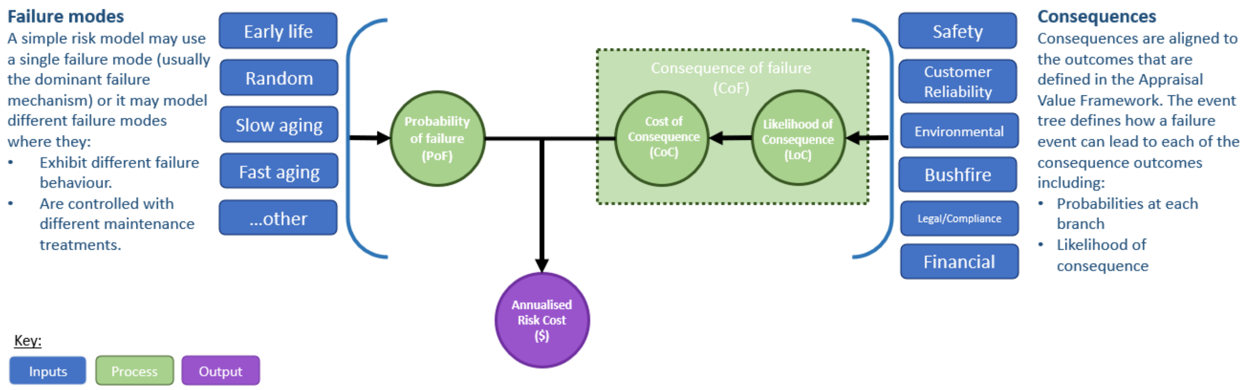
$$Risk\ Cost = Asset\ Probability\ of\ Failure \times Cost\ of\ Failure$$

Endeavour Energy has split this process into two parts:

- Probability of Failure (PoF) model, representing the actions leading to a failure including the cause and mitigations. PoF includes the impact of maintenance events.
- Consequence of Failure (CoF) model, representing the outcomes after a failure event. CoF does not typically change over the life of an asset.

A simplified quantative approach can be used to determine the risk that generally includes the following elements as shown in Figure 2 below.

Figure 2 - Risk cost elements

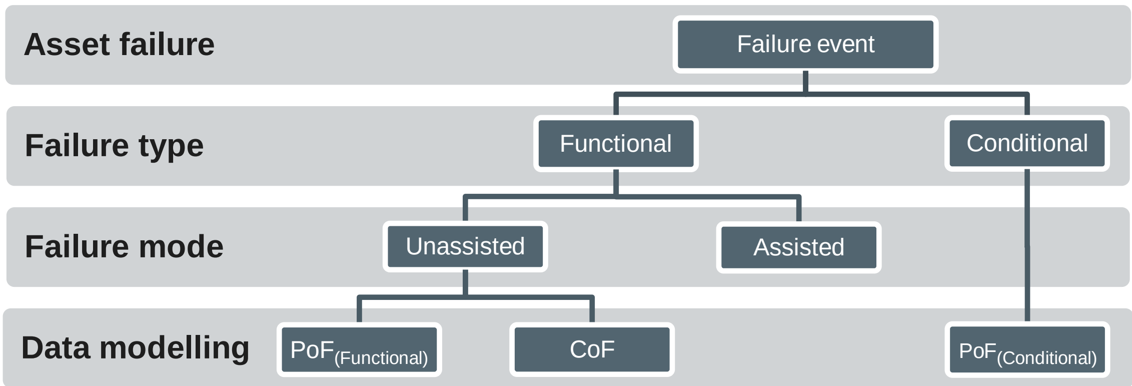


3.3 Asset failure

The evaluation of the PoF and the CoF within the risk cost methodology may be viewed as two separate calculation processes. However, they are both based on the same set of condition-based asset failure events (i.e., the same definition of what is failure). This is required to ensure the same set of potential events being considered in the assessment of probabilities and consequences.

For the purpose of this methodology, each asset failure is assessed to first determine its failure type and then its failure mode prior to determining the PoF and/or CoF model the data would be applied to. This is shown in Figure 3 below.

Figure 3 - Asset failure data used to calculate to PoF and CoF



These breakdowns are further explained in the following sub-sections below.

3.3.1 Failure type

Once a failure event has occurred, asset failures are initially assessed and grouped to one of the two failure type sub-categories as either a functional failure or a conditional failure. A brief definition of each of these failure types are described in Table 1 below.

Table 1 - Description of failure types

Failure type	Description
Functional	When an asset can no longer perform its intended function. The asset may have catastrophically failed or be partially operating in a degraded state but may not be capable of delivering all its required functionality. The asset may or may not be repairable.
Conditional	When an asset is showing symptoms of an imminent failure which may soon lead to a functional failure occurring. Typically identified through routine inspection or after the completion of a maintenance task.

The functional failures considered in the methodology are defined under each Asset Category and are recorded within its applicable Asset Class Plan.

Conditional failures are typically identified during routine inspection and maintenance activities and are defined in their applicable network standards.

3.3.2 Failure mode

In general, failure modes are all the mechanisms that contributed to the functional failure of an asset. Endeavour Energy has completed Failure Mode Effects and Criticality Analysis (FMECA) that have identified specific failure modes and have been used to develop appropriate maintenance strategies.

For simplicity, this repex risk-cost model classifies failure modes as either; assisted or unassisted, which had initially been assessed as a functional failure[1] and have not been eliminated through other management practices[2] . A brief definition of each of these two failure modes are shown in Table 2 below.

Table 2 - Description of failure mode

Failure mode	Description	Cause examples
Assisted	A functional failure that is caused by an external factor that was outside the design standards specified by the utility at the time of construction. They may affect all assets regardless of age or condition.	• Vegetation damage • Vandalism • Wildlife • Third party impact
Unassisted	The functional failure was caused by deteriorating asset performance over the life of the asset. Asset condition degrades over time and may be accelerated by environmental factors (E.g., temperature, humidity, etc.), general wear and tear, causing the probability of failure to increase over time.	• Cracking • Corrosion • Insulation degradation • Storms (within design limits)

[1] Asset Risk does not include interventions that are triggered by changes to required level of service

[2] Failure modes that have been effectively eliminated through maintenance strategy are not considered

3.3.3 Data modelling

To establish appropriate aged based functional failure forecasts, only events associated with unassisted failure modes are used for risk-cost data modelling. This approach aligns with the AER's definition, which excludes assisted failures when determining either their respective PoF or CoF.

Data from conditional failure types is used to generate a conditional PoF. This is used differently than that of the functional failure PoF. The conditional PoF assists in the modelling and forecasting of future condition-based reactive replacement quantities. However, under this scenario, as a conditional failure is identified and rectified prior to functional failure occurring they do not attract actual failure risk costs, so there is no associated CoF.

Descriptions of PoF and CoF are summarised further detail in Sections 3.4 and 3.5 below.

3.4 Probability of Failure (PoF)

The first key dimension of the risk-cost methodology is the consideration of the probability that the asset will fail. This is used in combination with an assessment of the consequence of asset failure to derive a single monetised value for network risk.

Endeavour Energy owns a vast range of assets that have different functions and perform under a range of different circumstances. Each of these assets can have very different life expectancies until an aged-based wear-out failure may occur.

The Probability of Failure (PoF) model has been developed using a repeatable statistical approach that allows the likelihood of failure for a similarly grouped asset type in a future given year to be forecast. This in part is completed by using past failure data to derive a relationship between the asset's age / condition and its probability of failure at that age. An introduction and overview of PoF is provided in the sub-sections below, with a more detailed breakdown provided in Section 4.

3.4.1 PoF Variants

The PoF is defined by a mathematical function that describes the relationship between the age and condition of an asset and likelihood of failure over a specified interval. This function can take many forms (See Appendix 1 – Probability of Failure Functions). However, the Weibull distribution is the preferred function used at Endeavour Energy focusing on the predominant failure mode.

Two types of PoF curves are derived for each asset type. One is to assess the likelihood of a conditional failure and the second is to assess the likelihood that a functional failure may occur. Each PoF variant has a specific use, their definition and examples of uses are shown in Table 3 below.

Table 3: Probability of failure variants

PoF Variants	Description	PoF use
$PoF_{(Functional)}$	Based on historical functional failure events the probability an asset catastrophically fails or be partially operating in a degraded state but may not be capable of delivering all its required functionality. Often separated into unassisted and assisted failures to improve the accuracy of ageing asset forecasts.	• Risk Calculations. • Proactive risk based targeted replacement forecast
$PoF_{(Conditional)}$	Based on historical condition-based replacements within the Endeavour Energy network. This is the probability that a defect is detected allowing for replacement to occur prior to functional failure. This	• Reactive condition-based replacement forecast

	evaluation is observed in line with the current maintenance and inspection strategies.	
$PoF_{(No\ Maintenance)}$	The probability of failure if no proactive maintenance is completed on an asset. Usually captured at the failure mode level and reliant on Original Equipment Manufacturer (OEM) input.	• FMECA • Reliability Centred Maintenance (RCM)

This document is primarily focused on risk cost as a result of functional failure event occurring, so PoF refers to $PoF_{(Functional\ Failure)}$ unless stated otherwise.

3.4.2 PoF adjustment

It is worth noting, that at times the PoF curve may be revised based on the treatment of the asset after a maintenance or failure event.

A functionally failed asset may be either repairable or non-repairable (e.g., requiring replacement). Within the model each asset type is categorised as either repairable or non-repairable[3]. This categorisation is based on standard post-failure practices by Endeavour Energy. A brief definition of repairable and non-repairable failure treatment is shown in Table 4 below.

Table 4 – Definition of failure treatment and its impact on PoF

Failure treatment	Description	PoF adjustment
Repairable	A repairable failure is defined as a situation where the failed asset can be returned to service following the replacement of a component/part of the asset, while retaining other components that were not affected by the failure.	No PoF adjustment. The repair is treated 'as- good-as-old' and the asset's PoF remains at the same value as it was before the failure[4].
Non-repairable	A non-repairable failure is defined as a situation where the failed components of the asset are not easily or efficiently replaced without replacement of the entire asset, so the entire asset (or a majority of) would require replacement.	PoF adjusted. The key result of a replacement is that the asset's PoF is reset to that of a new asset (the applicable PoF relating to the asset it has been replaced with).

3.5 Consequence of Failure (CoF)

The second key dimension of the methodology is the consideration of the consequence of an asset failure. As mentioned in the previous section, this is used in combination with an assessment of the probability of asset failure to derive a single monetised risk-cost value for network risk.

[3] This is a model simplification to reduce complexity. It is noted that some assets can experience both repairable and non-repairable failure modes. However, if both options were considered an additional optimisation function would be required to determine which action is taken, for each asset, for each possible failure year. Accordingly, this model considers only either a repairable or a non-repairable failure for each asset/asset type.

[4] Endeavour Energy are improving the modeling capability for repairable systems to consider partial renewals.

Endeavour Energy's assets are located in many different locations in New South Wales across Sydney's Greater West, the Blue Mountains, Southern Highlands, the Illawarra, and the South Coast. These assets operate under a differing range of circumstances such as with heavy industrial, commercial, or residential area's or located in a busy shopping centre, school zones or bushfire prone land.

The Consequence of Failure (CoF) is a probabilistic model that converts the range of possible consequence outcomes after a functional failure occurs into this single monetised value. These are typically evaluated based on historical data from actual failure events.

This simplified CoF calculation can be shown in the equation:

$$CoF = \sum_{consequecne\ category}^{category} \left(\begin{array}{l} [Likelihood_{outcome\ 1} \times Consequence\ (\$)_{outcome\ 1}] \\ +[Likelihood_{outcome\ 2} \times Consequence\ (\$)_{outcome\ 2}] \\ + \qquad \vdots \qquad \times \qquad \vdots \\ +[Likelihood_{outcome\ N} \times Consequence\ (\$)_{outcome\ N}] \end{array} \right)$$

This CoF equation is applied to each nominated risk consequence category to reflect the nature of different consequences arising from the failure of an asset. The total CoF for an asset, is the sum of all the different consequence categories assessed. To assist in this process, the model is developed using event tree analysis to visualise the events that can occur once a failure has been initiated. Each branch of the event tree requires:

- Likelihood of Consequence (LoC). The probability of that event (E.g., fire initiation) occurring given all the prior events on the tree have occurred; and
- Cost of Consequence (CoC). The termination of each branch is the cost of that event occurring (E.g., Cost of Major Bushfire) and aligns to consequence costs used across Endeavour Energy.

The calculation of the CoF is assessed on the same failure mode as the PoF.

3.5.1 CoF consequence categories

CoF consequence categories for use in the model are selected from a defined list of Value Measures. Each asset may encounter consequences associated with all or some of these Value Measures. This is to provide a consistent structured approach to risk consequence assessment.

These Value Measures are briefly outlined in Table 5 below.

Table 5 – CoF consequence categories

Value Measure	Description
Safety	Safety and health consequences to workers, public/consumers from an asset which results in a minor injury through to fatality. The consequence is typically expressed in terms of the Value of Statistical Life (VoSL)[5].

[5] In alignment with Australian Governments OBPR Value of statistical life.

Reliability	Loss or interruption of network electricity supply as a result of a functionally failed asset resulting in an unplanned customer outage. The consequence is typically valued via Value of Customer Reliability (VCR)[6] to the consumer type affected by the supply interruption.
Legal/Compliance	This refers to costs associated with a legal or regulatory/legislative compliance breach arising from the failure of an asset.
Environmental	Loss to the natural environment surrounding ecology, flora, and fauna and also the clean-up remediation following the failure of an asset.
Bushfire	Property damage and loss of life from a bushfire event that was initially ignited following the failure of an asset.
Financial	Costs arising from damage caused to other assets. Also, any other related costs that are not considered in other value measure consequences.

3.5.2 CoF adjustments

Once the monetised value of the CoF is calculated it is not typically adjusted over the life of the asset it has been calculated for. The CoF value will remain the same for the life of the asset. However, on occasion this may be re-evaluated if there is a significant impact resulting from a previously unknown failure mode or adjustment to the surrounding network that may affect the calculated outcomes of the Value Measures being applied.

3.6 Application of PoF and CoF to an asset

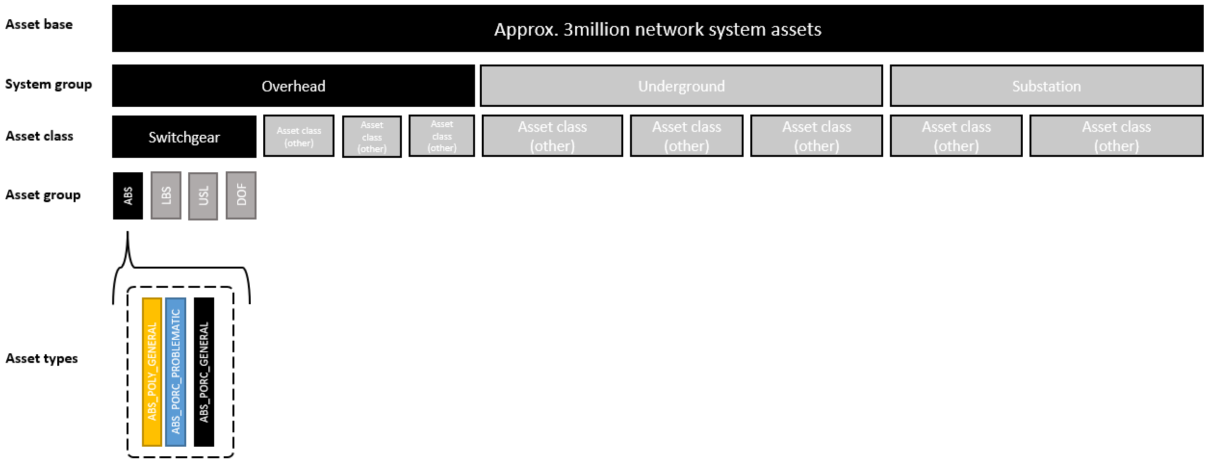
3.6.1 Asset hierarchy

This repex risk-cost methodology assesses an asset base of almost three million network assets involved in the distribution of electricity to end users, including transmission substations, zone substations, switching stations, distribution substations, poles and more than 47,000km of underground cables and overhead conductors and its associated equipment.

To assist in the asset management process, an asset hierarchy is created where the asset base is initially grouped into similar asset classes. Particularly with high volume low value assets. Asset types with like characteristics may be further merged under their respective asset classes. An example of this structure with particular attention to one asset class breakdown is shown in Figure 4 below.

[6] In alignment with the Australian Energy Regulator's (AER) published Value of Customer Reliability (VCR) report.

Figure 4 - Example of the asset hierarchy groupings for overhead switchgear assets



3.6.2 Asset types

The limited amount of site-specific data, more so for high volume assets (such as poles, conductors, and insulators) can make it problematic or unrealistic to have defined asset specific models, particularly for the measurement of the probability of failure.

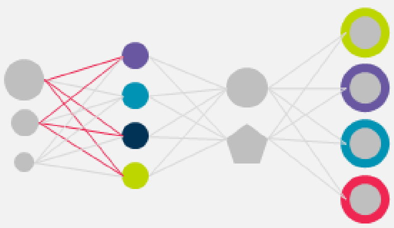
Asset Types provide a compromise that can improve the accuracy of forecasts and allow the minimal data on failures to be used across a population of like assets. Individual assets are assessed and matched to their closest asset types based on the considerations included in the list below:

- **Physical characteristics.** Assets that display similar dominant failure modes because of asset function, construction, or material type.
- **Locational factors.** Failure characteristics affected by acceleration factors caused by environmental conditions such as corrosion zone or temperature. E.g., with 5km of the coastline.
- **Intervention Cost.** Assets with a similar replacement / intervention cost are also grouped together. This is not a typical requirement for an Asset Type, however needed as part of the implementation of Endeavour Energy's risk model when assessing various intervention options.

It is worth noting that each new asset type introduced increases the number of models that need to be created and calibrated so is only considered where there is a material difference between the attributes being investigated. An example of the computational impact from increasing asset types is provided in Figure 5 below.

Figure 5 - Asset type computations

Consider an asset group that has four attributes (represented as 3 sizes, 3 colours, 2 shapes, and 4 borders) that may influence probability of failure. Covering all combinations would require 72 asset types to be modelled.



Reviewing the population reveals that attributes should be removed due to data quality limitations and insufficient failure data.

Assets can be matched the asset type that most closely matches the characteristics of an asset type that has been modelled.

Although asset information is continually improving for the current population, asset models are usually limited by the quality of historical data. As more asset information becomes available, it becomes possible to include more asset types; however, this is only completed once simpler models have been validated. Endeavour Energy have adopted a Crawl-Walk-Run philosophy to asset risk models, improving over consecutive iterations.

3.6.3 PoF application to assets

The limited amount of site-specific condition data for high volume asset populations make it problematic to have asset specific PoF models (Power Transformer being one exception). For this reason, Asset Types are used to allow the modelling of an assets PoF.

Individual assets are matched to the closest asset types (as per guidelines outlined in Section 3.6.2) and are assumed to match the PoF model of the asset type.

3.6.4 CoF application to assets

In most instances, CoF can be calculated at an individual asset level due to the availability of data from both internal and external sources, meaning that every asset in the network has a CoF that considers its context in the network.

3.7 Annualised risk costs

Once the PoF and CoF have been determined, the annualised risk cost of an asset can then be modelled into the future using the risk-cost calculation equation.

This risk cost is a per year monetary value. It is based on an asset failing in a future financial year. Each year that passes, the annual risk cost increases. This increase is typically in relation to the PoF due to its rising failure rate over time assuming that the asset has survived to that future year.

The risk cost for non-repairable assets for any given year does not exceed the total value of its calculated CoF. As the PoF would not exceed one functional failure event over the life of the asset. It works on the assumption that when the asset functionally fails it is removed from service with the consequence event only occurring once.

This is different for repairable assets where the PoF may exceed one functional failure event over the asset's lifetime. Noting that the asset may fail multiple times in a given year, be repaired as-good-as-old and put back into service. Meaning the consequence may reoccur on any subsequent future functional failures.

3.8 Asset Retirement and proposed investment

3.8.1 Hurdle Rate and NPV method

Endeavour Energy uses two investment methodologies for determining whether an investment is worthwhile and justified from an economic perspective. The first is a hurdle rate method, which is simple to implement and computationally simple.

This method is used by the AER as it provides a quick check that proposed investment is efficient by pointing to the optimum time for investment. Given its simplicity however, it may not always give accurate results, particularly with assets with complex and interdependent failure modes.

The second is the Net Present Value (NPV) method which provides the NPV of investment over a range of years.

Both methods are used by Endeavour Energy in assessing the value of proposed investment.

3.8.2 Proactive intervention proposal

With the hurdle rate method an investment is justified if the risk and other costs (such as opex) mitigated in the first year is greater than the cost of financing the investment for that year.

The basis of the NPV approach is modelling the deferral of the investment until the eventual failure of the existing asset and the realisation of the risk associated with its failure (as well as to gain any other benefits such as reduced consequences of failure, reduced opex and better performance which may be provided by the modern equivalent replacement asset).

An investment is economic if the deferral value is greater than the cost of the investment. The modelled investment year is deemed optimal for intervention timing when the NPV is at its maximum value across the calculation horizon.

The purpose of this approach is not to avoid risk, as this would require ongoing replacements of future generations of the asset into perpetuity or decommissioning the asset entirely, which is a highly uncertain proposition in terms of outcomes and beyond the scope of this model.

3.8.3 Sensitivity analysis

The purpose of sensitivity analysis is to communicate the impact / uncertainty model inputs have on the confidence of the modelling results. The primary use case for sensitivity analysis is to:

- Determine whether an investment recommendation will change if the inputs differ from the expected value.
- Determine the impact an assumption has on outputs and assign a priority for replacing it with quantitative analysis where it is found to have a material impact on recommendations.

3.8.4 Reactive replacement

Some asset classes may be operated run-to-failure because the assets have a low risk, high cost of intervention or cannot be reliably identified before failure. In asset classes where proactive investment does occur, not all assets may be caught before they fail.

The expected number of asset failures within an asset class is equal to the sum of the PoF across all assets in that asset class. The PoF of any assets proposed to be proactively replaced (e.g., have reached their maximum NPV) are removed from the calculation. This establishes the relationship between planned and reactive asset replacements and allows changes in the planned program to be modelled in the corresponding reactive forecasts.

Since it cannot be predicted which asset will reactively fail, the model currently assumes that failures occur in the units that have the highest PoF. This is an optimistic view of asset failures as it results in the greatest amount of risk being removed from the network, as the risk removed is equal to PoF times the average consequence value (assuming the new asset has zero or near zero PoF).

3.8.5 Case for investment

A case for investment (CFI) recommends proactive and reactive investment in the replacement of specific asset types across the network during a defined period (e.g., FY25 – FY29) to address the safety, reliability, environmental, bushfire, legal/compliance and financial risks associated with this equipment failing whilst in service.

The CFI recommends these investments to be included into the portfolio risk-based asset investment planning and optimisation process.

Within the recommended program of works, each asset has been assessed individually for the risk it presents.

3.8.6 Application of RIT-D

When undertaking this cost benefit analysis, Endeavour Energy gives due consideration to what intervention options are available (inclusive of non-network options), before identifying the best way to address needs on the network through the application of the RIT-D process.

4. Probability of Failure

The first key dimension of the risk-cost methodology is the consideration of the probability that the asset will fail. This is used in combination with an assessment of the consequence of asset failure to derive a single monetised value for network risk.

Endeavour Energy owns a vast range of assets that have different functions and perform under a range of different circumstances. Each of these assets can have very different life expectancies until such time an aged-based failure may occur.

The Probability of Failure (PoF) model has been developed using a repeatable statistical approach that allows the likelihood of failure for a similarly grouped asset type in a future given year to be forecast. This in part is completed by using past failure data and available conditional data to derive a relationship between the assets age and its probability of failure at that age.

PoF is defined by two key components:

1. The form of the distribution function (E.g., Weibull distribution); and
2. The numerical value of the parameters of the function.

This section will detail the methodologies of the probability distribution functions used by Endeavour Energy and determination of the input parameters when developing the PoF for our various asset types.

4.1 PoF distribution function

A PoF function is an equation that relates one or more characteristics of each individual asset to the probability of its failure (PoF).

While the PoF function can take many forms (see Appendix 1)[7] the default PoF Function used in the Endeavour Energy Risk Models is the Weibull distribution. It is commonly used in the Australian electricity industry and is suggested by the AER in the *Industry practice application note for asset replacement planning*[8]*.*

In a small number of asset groupings, Endeavour Energy applies the Common Network Asset Indices Methodology (CNAIM)[9] where the additional data required to undertake this method is available.

The applications of both the Weibull distribution function and the CNAIM models in determining an appropriate PoF are explained in section 4.2 and 4.7 below.

Note: The applicable PoF functional form is decided at an asset class level. Each asset within the asset class is assumed to exhibit the same relationship between condition and failure rate. Where this does not hold then the asset class should be split into asset types with unique PoF functions.

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[7] Industry standard PoF functional forms and approaches to estimation of the parameters are presented in

[8] https://www.aer.gov.au/system/files/D19-2978%20-%20AER%20-Industry%20practice%20application%20note%20Asset%20replacement%20planning%20-%2025%20January%202019.pdf

[9] https://www.ofgem.gov.uk/sites/default/files/docs/2021/04/dno_common_network_asset_indices_methodology_v2.1_final_01-04-2021.pdf

4.3 Application of the Weibull distribution function

4.3.1 Weibull Functional Form

The Weibull distribution is a continuous probability distribution that can fit an extensive range of distribution shapes. There are two versions of the Weibull distribution. The three-parameter Weibull distribution, which has three parameters, shape, scale, and shift. When the shift parameter is set to zero, it is known as the two-parameter Weibull distribution.

The starting point used for the development of each Weibull distribution for each asset type is the Cumulative Distribution Function (CDF) which presents the cumulative probability an asset has failed by a given age. This is shown in the following equation:

$$CDF = 1 - e^{\left(\frac{t-\gamma}{\alpha}\right)^{\beta}}$$

Where the three parameters are:

$$\begin{aligned}\alpha &= Weibull\ scale\ parameter\ (or\ characteristic\ life)\\ \beta &= Weibull\ shape\ parameter\ (or\ slope)\\ \gamma &= Weibull\ shift\ parameter\ (or\ failure\ free\ life)\end{aligned}$$

And *t* is the age of the specific asset under evaluation.

For assets that are described by a continuous distribution a PoF interval needs to be defined. Once the CDF has been calculated it can be converted from a cumulative probability into a probability of failure for a given year of age (defined as the age of the asset at the end of the year rounded to the nearest whole number). Endeavour Energy refers to this as the Hazard Rate and is shown in the equation below:

$$Hazard\ Rate = \frac{CDF_{age} - CDF_{age-1}}{1 - CDF_{age-1}}$$

Note: The Hazard Rate is conditional on the asset surviving to the year before the age the asset PoF is being evaluated at. It does not consider whether the asset has already failed before that point in time.

This variant of PoF does have its limitations when applying the results into an asset investment methodology. There are two methodologies Endeavour Energy uses for determining whether an investment is worthwhile and justified from an economic perspective.

The first is a hurdle rate method, the second is the Net Present Value (NPV) method. Both methods are used by Endeavour Energy in assessing the value of proposed investment. They are explained further in Section 6.

The Hazard Rate is appropriate for calculations where survival can be assumed. This includes when applying the hurdle rate method[10] or when applying the NPV method to a *repairable asset*[11].

However, the limitation is in relation to the Hazard Rate which cannot be used for when applying the NPV method to a *non-repairable* asset.

[10] The hurdle rate method only uses the calculation of risk in the first period (i.e., year) after the investment to determine whether to invest. This means the asset is guaranteed to exist in the year before the calculation takes place (otherwise the investment decision would not be available).

[11] On failure, the asset will be repaired and the PoF will continue to increase, rather than being reset to the PoF of a new asset. Over the forecast horizon, a repairable asset may fail multiple times. This is not true of a non-repairable asset.

This is because the NPV method requires the forecast of future risk associated with the asset, which requires the inclusion of the probability the asset has failed and been replaced at any point in the forecast period. Instead, for non-repairable assets the NPV method requires the relative probability the asset will fail in each year.

The relative probability the asset will fail in a given year is equivalent to the probability density function (PDF) of the PoF function. For a Weibull function, a standard formula is available for the PDF, but this calculates the instantaneous probability of failure. As the model requires the PoF over a one-year period (rather than instantaneously) the PoF should be calculated from the CDF[12].

For a brand-new asset, this is simply the change in the CDF for each year of age:

$$PDF \cong CDF_{age} - CDF_{age-1}$$

Most assets being modelled are not brand new at the point in time when an investment is being considered. As they have already survived to a particular age, we are observing survivors rather than the entire population of each cohort. To account for this, the PoF Function needs to be adjusted to:

$$Relative\ PDF = \frac{CDF_{age} - CDF_{age-1}}{1 - CDF_{current\ age}}$$

Properties of the Relative PDF:

- Similar to the PDF (but over a year rather than a single point in time);
- Calculated from the CDF as it provides points in time;
- Change in CDF over a year is divided by 1-CDF at the start of the year. In effect the percentage of the survivors at the start of the year that are not alive at the end of the year;
- This *Relative* adjustment ensures that the sum of PoF values over all ages above the current age sum to 100%;
- Used where the failure mode assigned to the asset is described as non-repairable because the asset is guaranteed to fail once and only once.
- Failures after the first failure are not considered because our decision is limited to the asset that is installed after the decision (either the existing asset or a new/refurbished asset)
- The output provided by this Relative PoF can now be used in the NPV investment calculation method for a non-repairable asset.

At Endeavour Energy, unless defined otherwise, discrete, and linear assets comply to the following rules:

- **Discrete Assets.** The PoF is considered over a single year prior to time $(t-1 < T \leq t)$
- **Linear Assets.** As per discrete assets, but PoF is adjusted proportionally for the length of asset to give a failure rate per year per km. As most linear assets at Endeavour Energy are repairable, the PoF for a linear asset may exceed 100% (e.g., it may fail multiple times along its length) if the asset is sufficiently long.

This allows the Hazard rate, PDF, and Relative PDF to be expressed as a discrete probability in terms of the CDF which removes the need to solve integrals. A summary of these Weibull PoF functions and their application are shown in Table 6 below.

[12] For a typical Weibull function, PoF increases with age so that the PDF at the start of the year may be significantly higher than the PDF at the end of the year. The approach using the CDF is approximately equal to the PDF at age minus 0.5, as the midpoint is close to the average over the year.

Table 6 - Summary of Weibull PoF function selection for an asset

Failure treatment	Asset age	Weibull PoF function	Investment methodology
Non-repairable	New	$PDF \cong CDF_{age} - CDF_{age-1}$	NPV
	Existing – current age today	$Relative\ PDF = \frac{CDF_{age} - CDF_{age-1}}{1 - CDF_{current\ age}}$	NPV
	Existing - age at deferred investment year	$Relative\ PDF = \frac{CDF_{age} - CDF_{age-1}}{1 - CDF_{(current\ age+deferral\ years)}}$	NPV
Repairable	New or Existing	$Hazard\ Rate\ = \frac{CDF_{age} - CDF_{age-1}}{1 - CDF_{age-1}}$	NPV or Hurdle

Figure 6 below shows an example of these various Weibull PoF functions for a brand-new asset.

Figure 6 - Weibull probability functions for a new asset

Example. An asset at age zero defined by a Weibull distribution with the parameters $\alpha = 25, \beta = 3.6, \gamma = 0$ is shown below.

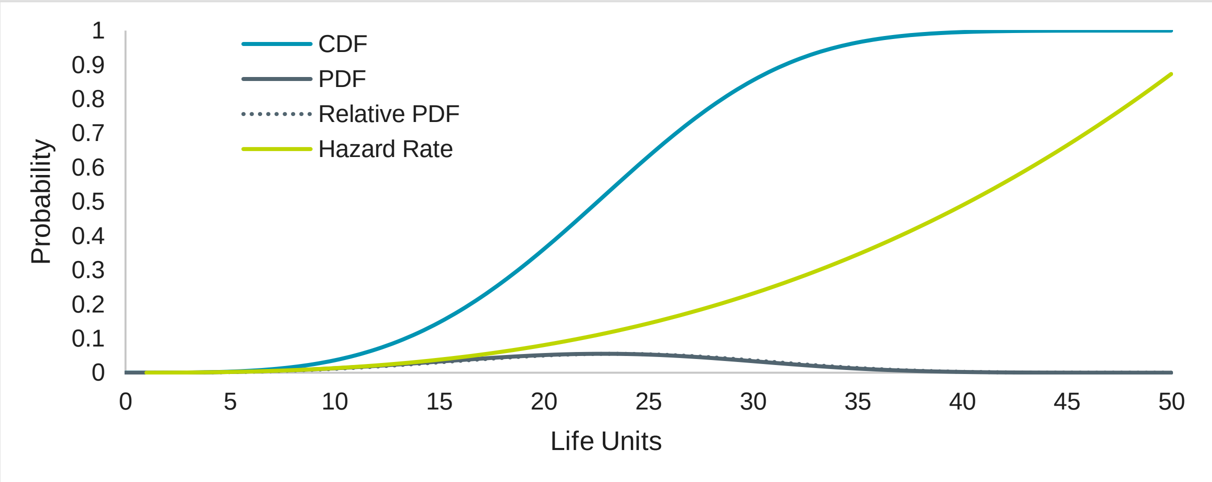
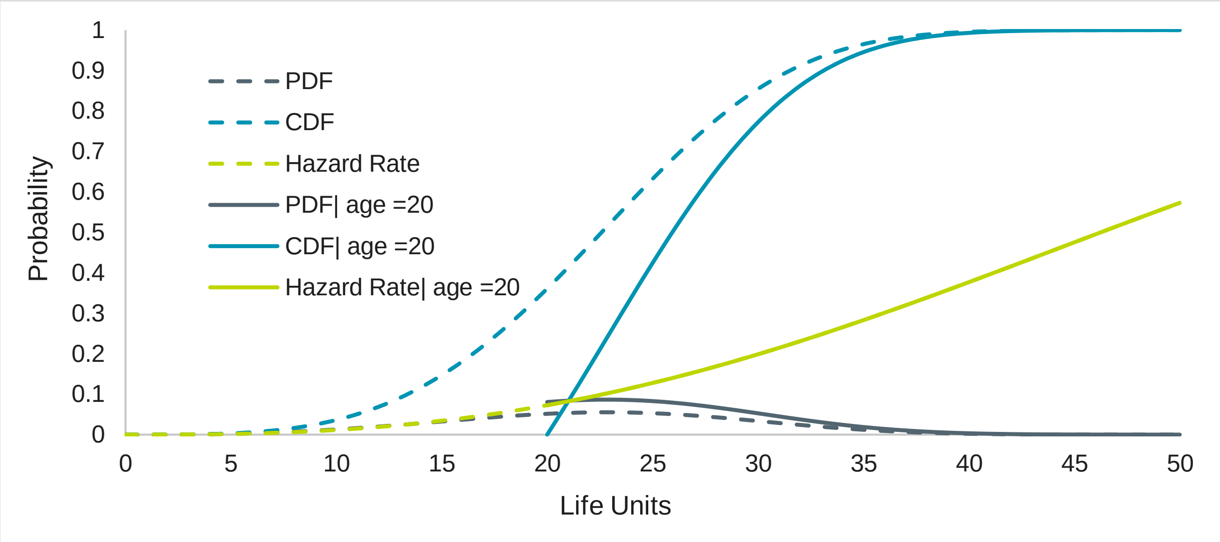


Figure 7 below shows an example of these various Weibull PoF functions for an existing asset where its current age is 20 years old.

Figure 7 - Weibull probability functions for a 20-year-old asset

Example. Consider an asset at age 20 with a PoF defined by a Weibull distribution with the parameters $\alpha = 25, \beta = 3.6, \gamma = 0$. The conditional PoF remains the same; however, the CDF and PDF for this asset have changed to remove the probability that the asset has already failed. This gives a steeper rate of change to the probability function.



4.4 Weibull distribution parameter estimation methods

Endeavour Energy estimate Weibull parameters for an asset class and/or an asset using a life table and a variety of analytical and empirical methods where the three parameters are:

$$\alpha = Weibull\ scale\ parameter\ (or\ characteristic\ life)$$
$$\beta = Weibull\ shape\ parameter\ (or\ slope)$$
$$\gamma = Weibull\ shift\ parameter\ (or\ failure\ free\ life)$$

Endeavour Energy's preferred established bottom-up methods for estimating these are:

- Least Square Regression (LSR); and
- Maximum Likelihood Estimator (MLE).

Other methods available for use also include:

- Method of Moments (MoM); and
- Weighted Least Square Regression (WLSR).

Each of these methods have advantages and disadvantages that affect their accuracy in some scenarios. At Endeavour Energy we use a combination of methods and SME guidance to select the parameters that best represent the failures being modelled.

An additional top-down method calculates the scale parameter that is needed to match the observed annual failure rate when default values are used the shape ($\beta = 3.6$) and shift ($\gamma = 0$) parameters.

The results of these methods provide a starting point for manual selection and review. Where there are major differences between analytical methods, further calibration is recommended.

4.4.2 Least Square Regression (LSR)

Ideal for small samples of data. LSR leverages commonly used regression techniques to determine a shape and scale parameter.

The CDF of the Weibull distribution can be rearranged to take the form for a linear equation $y = mx + b$.

$$F(t) = 1 - e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$$

$$\underbrace{\ln\big(-ln\big(1 - F(t)\big)\big)}_{y} = \underbrace{\beta \ln t}_{mx} - \underbrace{\beta \ln \alpha}_{b}$$

Linear regression can then be used to find the slope and intercept of that provide the best fit of the data.

$$\beta = \text{gradient}$$

$$\alpha = e^{-\frac{\text{intercept}}{\beta}}$$

4.4.3 Maximum Likelihood Estimator (MLE)

Ideal for larger samples and heavily censored data. Finds the most likely parameters (3 parameter or 2 parameter) using a likelihood equation.

Numerical optimisation (E.g., Excel Solver) is used to find the Weibull parameters that maximise the Log likelihood equation:

$$LL(t, \alpha, \beta, \gamma) = -m\left(\frac{t_i - \gamma}{\alpha}\right)^{\beta} + n[\ln \beta - \beta \ln \alpha] + (\beta - 1)\sum_{i=1}^{n} \ln(t_i - \gamma) - \sum_{i=1}^{n}\left(\frac{t_i - \gamma}{\alpha}\right)^{\beta}$$

4.4.4 Method of Moments (MoM)

Can be used to generate an initial estimate for α and β that are used by other numerical methods

The mean and standard deviation can be solved using:

$$\mu = \alpha\Gamma\left(1 + \frac{1}{\beta}\right)$$

$$\sigma^2 = \alpha^2\Gamma\left(1 + \frac{2}{\beta}\right) - \mu^2$$

Taking the natural log of μ and σ^2 and eliminating σ algebraically gives

$$ln\Gamma\left(1 + \frac{2}{\beta}\right) - 2ln\Gamma\left(1 + \frac{1}{\beta}\right) - \ln(\sigma^2 + \mu^2) - 2\ln \mu = 0$$

Use numerical methods to solve for β and then solve for the following equation for α

$$\alpha = \frac{x}{\Gamma\left(1 + \frac{1}{\beta}\right)}$$

4.4.6 Weighted Least Square Regression (WLSR)

An extension of least square regression that applies a weight to each data point to reflect different standard deviations.

The scenarios where WLSR can be useful are:

- A new asset type is introduced that behaves more like an existing asset type than the others. Weighting allows a preference to be applied to an
- We have higher confidence in some measurements based on known differences in accuracy (E.g., faulty meters, improved oil sampling methods, more accurate inspection tools, etc.)

However, the best fit requires high level of data of the asset reliability.

4.5 Derivation of parameters for an asset class and/or individual asset

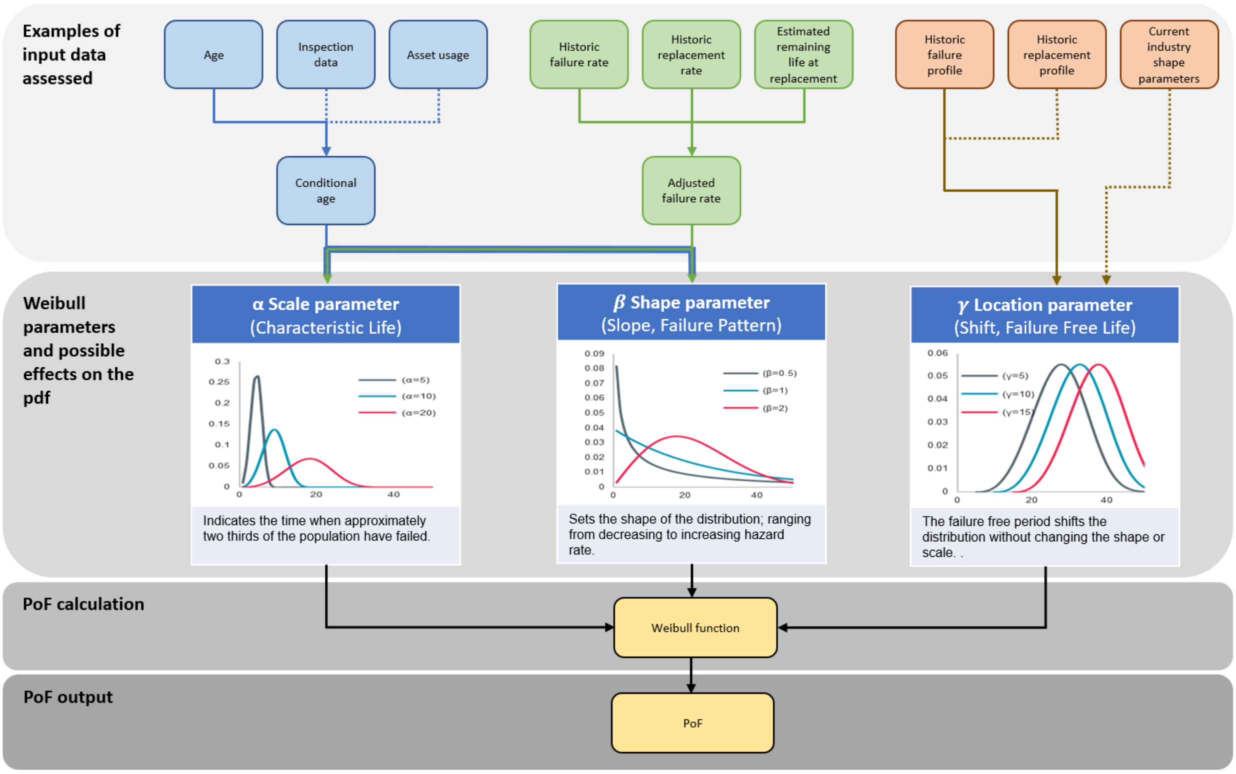
Accurate parameter estimation requires a record of every asset. Asset data is derived from Endeavour Energy's own records or from industry data or a combination of the two. The data includes the assets age and enough information to determine whether it should be treated as a failure event or should be censored. The survival data should include the current population and all historical assets that have been removed from service for any reason including functional failures, conditional failures, and retirements.

Where possible, a failure mode should also be included to determine how to classify a failure depending on the event being investigated.

The objective is to obtain sufficient age-at-failure data for the asset class or individual asset to be statistically valid as a basis for deriving the probability of failure time series for that asset or asset class.

Typical asset data inputs used for the calibration of the parameters and development of the PoF is shown Figure 8 below.

Figure 8 - Asset data used to calibrate Weibull parameters



Network datasets are often characterised by highly censored data. Assets may have been replaced before they had the chance to fail or have not yet failed (right censored) or the failures were not correctly recorded, usually due to the installation date not being known (likely to be left-censored). Most networks only have reliable failure data for the few most recent years, which is a significant driver of this issue.

The process in gathering and evaluating asset data for estimating Weibull parameters typically follows these stages:

1. Gathering of survival data;
2. Generating a life table;
3. Calibration period adjustment;
4. Fitting the Weibull distribution and validating the outputs
5. Manually adjusting the Weibull CDF parameters where required to better fit the outputs.

Noting: Over time, more data of a sufficient quality may be collected, which may enable a revisiting of the estimation of the Weibull parameters.

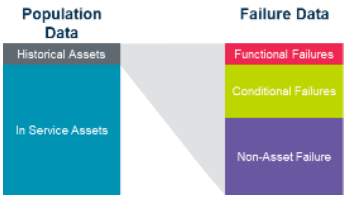
4.5.1 Gathering survival data

Table 7 illustrates the typical process for the gathering and refining of asset data from Endeavour Energy's own records for asset classes and individual assets.

Table 7 - Asset class and/or asset survival data gathering

<table>
<tr><th>Step</th><th>Description</th></tr>
<tr><td>Step 1 – Gather Data
<table><tr><th>Asset ID</th><th>Age</th><th>In Service</th><th>Failure Mode</th></tr><tr><td>111</td><td>19</td><td>Yes</td><td></td></tr><tr><td>112</td><td>35</td><td>No</td><td>Upgrade</td></tr><tr><td>113</td><td>23</td><td>No</td><td>Lightning Strike</td></tr><tr><td>114</td><td>49</td><td>No</td><td>Degradation</td></tr><tr><td>115</td><td>33</td><td>No</td><td>Fire Damage</td></tr><tr><td>116</td><td>28</td><td>No</td><td>Degradation</td></tr></table></td><td>Gather the age and failure mode for all assets that have been in service including the current and historical population. All assets that have been removed from service should be included as these censored values are used in the Weibull fit. Examples include:
Asset Failures
Functional
Conditional
Asset Replacements
Past strategies and criteria
Asset Retirements
Recommendation: Gather data from all asset management systems</td></tr>
<tr><td>Step 2 – Remove invalid data</td><td>While every effort should be made to retain most data, incorrect data fields should be changed to unknown. Unknown data will need to be removed for some analysis (E.g., life data), but should be added back into the total population wherever possible.
Recommendation: Filter data aggressively initially and review in more detail during subsequent iterations</td></tr>
<tr><td>Step 3 – Define Asset Types
</td><td>Select Asset Types for the asset class that reflect the underlying probability of failure models. The understanding of attributes that impact asset performance often exceeds the availability of data to model all asset types. Asset types with young populations relative to the expected asset life or with limited failure data are unlikely to produce good fits and should be used with caution. In most instances, better outcomes can be achieved by combing asset types to produce a confident fit, rather than adding granularity through asset types.
Recommendation: Start with the concise asset types focusing on physical characteristics and expand asset types during subsequent iterations.</td></tr>
</table>

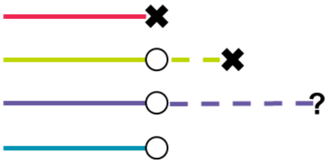
Step 4 – Define the event



The event of interest is usually a functional failure; however, in some instances it may be more targeted to unassisted / assisted failures or to a specific failure mode. Correctly identifying the reason for removal from service increases the scope for modelling probability of failure. All assets that have not been impacted by the defined event are considered censored assets for the remainder of this analysis.

Recommendation: Focus on Unassisted Functional Failures first as this has the greatest influence on risk-based investment decisions. Consider assuming the assets are affected by a single dominant failure mode

Step 5 – Adjust censored data



While the aim is to remove conditionally failed asset from service as close to failure as possible, for risk and operational reasons, these assets are often retired when the asset has remaining useful life. Where remaining useful life of an asset is known, the asset age can be increased by the time to failure.

Recommendation: Only consider where P-F Interval is well understood.

4.5.2 Generating a life table

Two non-parametric methods can be used to account for censored and generate a Life Table. These techniques are commonly used in most reliability software packages.

Table 8: Life Table Methods based on Data Availability

Data Availability	Method	Examples
Complete	**Kaplan-Meier**. A non-parametric method for estimating the Survival Function. It is the most popular method and produces accurate results with complete data.	Asset classes with accurate records (e.g., *Transformers)*
Partial	**Nelson-Aalen.** A non-parametric method for estimating the Cumulative Hazard Function. Typically used to determine the hazard rate over a defined period (E.g., one year). Preferred method for large data sets where accurate failure data is only available over a specific calibration period.	Asset classes that pre-date modern EAMs (e.g., *Poles)*
Limited	**Expert Elicitation.** Where failure history is unavailable, or is not considered reliable, the Weibull will need to be estimated. SMEs should use their knowledge of comparable assets, guidance from the OEM and the industry understanding of asset performance in similar conditions. This information should be used to benchmark the parameters estimated using expert elicitation	New asset classes, non-serially tracked assets (e.g., *SAPS, Pole Top Equipment)*

At Endeavour Energy the Nelson-Aalen method is used for most asset classes due to limitations around data quality.

4.5.3 Calibration period adjustment

Incomplete data decreases the accuracy of a parameter estimation, particularly for non-homogenous populations. To address these issues an adjustment can be made to the hazard rates or failure/censor counts to reflect the calibration period used.

Some common causes:

- Failure data has not been recorded for the entire fleet life (E.g., Failures have only been recorded for 5 years yet there are assets older than this in service)
- An aging population where most assets are approaching the end of life. This can occur when an asset type is no longer installed on the network but remains in service. (E.g., most assets are 20-30 years old)
- Selection of a calibration period that is not a perfect sample of the assets being investigated. (E.g., changed maintenance strategy, black swan events)

A hazard rate adjustment should be made to the life data prior to fitting the Weibull when the failure data available / selected is not an accurate sample of the failures for that asset class. This most often occurs when the assets have an inconsistent age profile and failure data is unreliable or incomplete.

For each age bin:

1. Calculate the number of assets that survived past that age. For each age, t, it is the sum of the population, i, currently in service older than t.

$$number\ of\ assets\ alive_t = \sum_{x=0}^{t_{max}-t} i_{t+x}$$

2. Calculate the number of assets that were age t at any time during the calibration period. For each age t, sum the population, i, where $\{(t) |\ t < t + t_{calibration}\}$.

$$number\ of\ assets\ alive\ during\ calibration\ period_t = \sum_{x=0}^{t_{calibration}} i_{t+x}$$

3. Calculate the percentage of assets that are considered during the hazard rate.

$$scale\ factor_t = \frac{number\ of\ assets\ alive\ during\ calibration\ period_t}{number\ of\ assets\ alive_t}$$

4. Scale the number of failures and the number of censored assets by the scale factor for each age, t.

$$failures\ adjusted_t = \frac{failures_t}{number\ of\ assets\ alive_t} \times scale\ factor_t$$

$$censored\ adjusted_t = \frac{censored_t}{number\ of\ assets\ alive_t} \times scale\ factor_t$$

Applying the scale factor increases hazard rate for younger assets which decreases the slope of the shape parameter and improves the accuracy of the failure rate across all asset ages.

Example. Consider an asset class that has been in service for 50 years; however, functional, and conditional failures have only been recorded accurately for the last 10 and 15 years respectively. Any failures that occurred prior the calibration period (pre-2005) have not been recorded (see Figure 9). The lower observed hazard rate for younger assets increasing the proportion of older failures and gives the appearance of a more aggressively increasing hazard rate (see Figure 10). Scaling the hazard rate based on the calibration period corrects the difference between the real and observed failure rates.

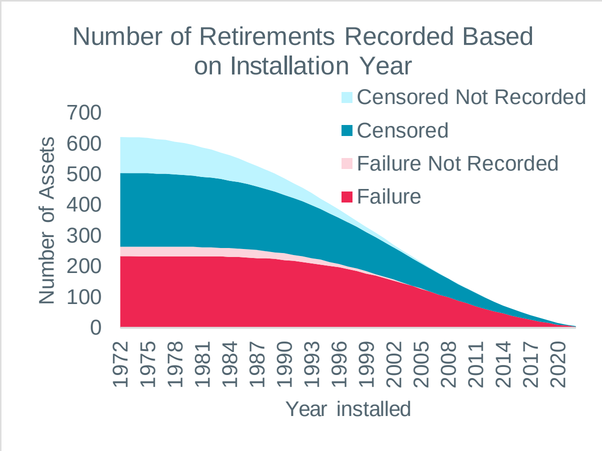


Figure 9: Missing Failure Data

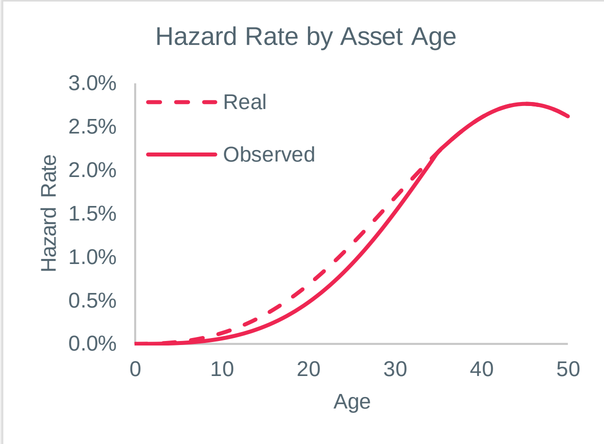


Figure 10: Scaled Hazard Rate

4.5.4 Fit the Weibull distribution and validate output data

Fitting a Weibull distribution to event data is a well understood process that gives repeatable results. Most of the effort involves calibrating the selected parameters and ensuring the risk forecasts align with historical actual events. Calibration is a systematic process that involves choosing appropriate inputs, selecting the most appropriate methods, and validating forecasts against known outputs.

Regardless of the method used, it is important to validate the Weibull parameters against the current population and comparing to any observed outputs:

Table 9 - Parameter calibration table

Metric	Calibration Method
Annual Failure Rate	Calculate the number of failures that would occur over one year with the current population and compare this to the failures that have been observed.
Planned Work	Compare the number of replacements forecast with the volume of planned work.
Asset Health	Does the number of assets in poor health, align with the number of functional and conditional failures?
Maintenance Events	Are maintenance events trending in the same direction predicted by the forecast?
Forecast Failures	Calculate the number of failures that are expected to occur over the next regulatory period with the current population and compare to the failures forecast by the AER Repex Model
Risk Events	Do the number of risk events (E.g., Fatalities, Bushfire starts, etc.) align?

4.5.5 Calibration

PoF calibration is completed by comparing the results of the bottom-up model to top-down model outputs and historical actuals.

If the model is not considered accurate following the validation and common issues have been investigated, consider manually adjusting the Weibull parameters using the following techniques.

Table 10: Weibull Parameter Calibration – Common Issues

Issue	Possible Cause	Solutions
The line of best fit on the Weibull Probability Plot does not match the failure data	**Asset Types**. There may be multiple asset types that experience different failure modes.	Review the asset types selected ensuring that enough failures are observed for each asset type
	Failure Modes. The asset class may be affected by several distinct failure modes that should be modelled separately (E.g., a slow aging and fast aging failures that initiate several years apart).	Separate failure modes ensuring the enough failures are observed for each failure mode. For most asset classes, data maturity will only support separating assisted and unassisted failures.
	Acceleration Factors. Identical assets degrade at different rates due to environmental or load factors.	Separate assets by based on acceleration factors (E.g., location, etc.)
Failures are too low/high	**Probability of Failure Model.** Weibull parameters are incorrect.	Review the Weibull parameter estimation.
Risk events are too low/high	**Consequence of Failure Model.** LoC values are incorrect.	Review the LoC parameters.

It will be necessary to estimate the Weibull parameters manually if:

- Insufficient data is available to fit the data using analytical methods;
- There is low confidence in the accuracy of the available data; or
- The parameters estimated by different analytical methods are significantly different.

4.5.6 Manual parameter adjustment

The analytical methods for estimating PoF function parameters are sensitive to censored data and may require manual adjustment. If the results forecast does not match the Weibull parameters need to be adjusted so it matches the risk profile that has been observed with the current asset population. The failure Weibull parameters should be adjusted in the following order;

Table 11 - Calibration order

Step	Parameter	Actions
1	Shift	Check if early failures are correct and, if in doubt, set to zero.
2	Shape	Check if the expected failures match across all ages. If the failures are: • Too low for young assets and too high for old assets – Decrease Shape • Too high for young assets and too low for old assets – Increase Shape
3	Scale	If the failure trend matches, but the overall number of failures is: • Too low – Increase the characteristic age • Too high – Decrease the characteristic age

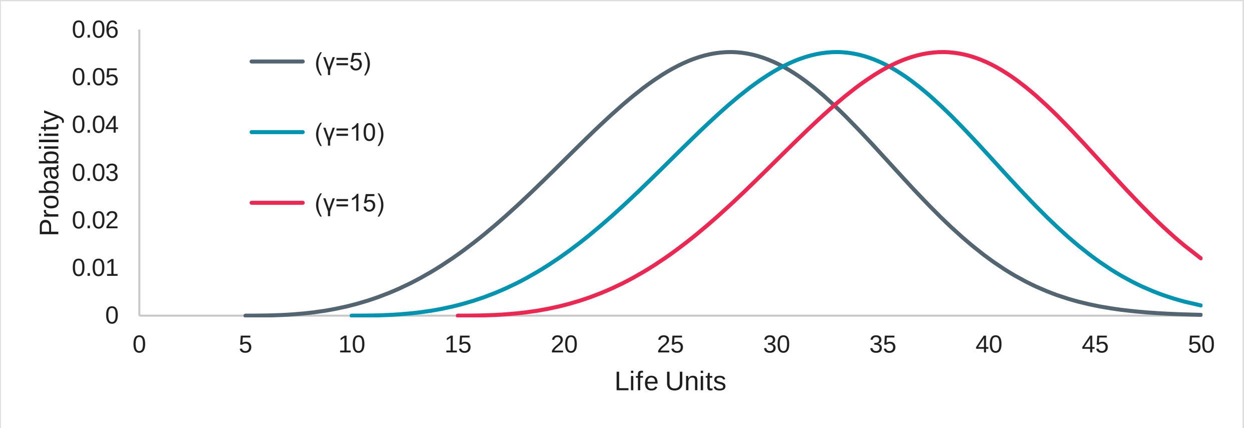
4.5.6.1 Shift Parameter

The shift parameter γ provides an estimate of the earliest time at which a failure may be observed. Changing the value of γ has the effect of sliding the Weibull probability distribution and its associated function to the right (γ > 0) or to the left (γ < 0). The failure free period shifts the distribution without changing the shape or the scale.

When γ = 0 then the Weibull probability distribution starts at zero. When a value for γ is set above zero, no failures occur before γ years and the timescale starts at γ and not zero.

Where γ < 0 it would suggest failure may have occurred during production, in storage, in transit prior to actual use. This would not be considered an age based conditional failure. Failures of this nature are not included as part of this assessment.

Figure 11 – Impact on the PDF by varying the shift parameter γ



For the purpose of Endeavour Energy's assessment, the default shift parameter used should be zero, unless there a sufficiently large sample of failures and strong consensus from either subject matter experts or other asset users that a failure free period exists for the failure event being investigated. The shift parameter can be estimated from a sample of failure data using the following formula:

$$shift = Min(failure\ age) - \frac{1}{n}$$

Where:

$failure\ age =$ ages of all failed assets at the date of failure
$n =$ number of failures

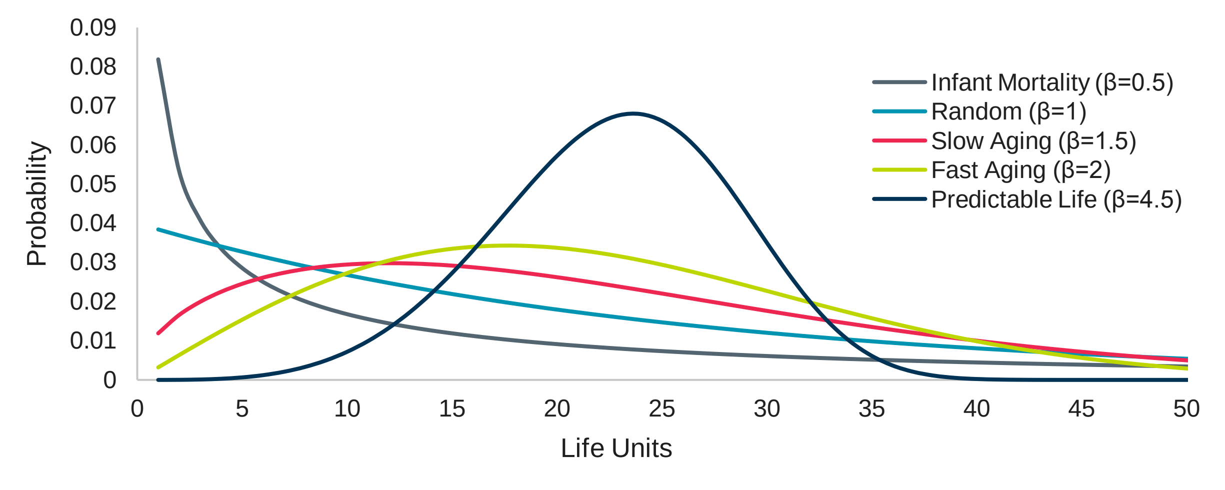
As n becomes large, this is equivalent to setting the shift parameter to the age of the youngest observed failure for each asset class. For any value on n where the final term doesn't become very small there is likely to be too much uncertainty for the result to be used.

4.5.6.2 Shape Parameter

The shape parameter β of a Weibull distribution represents the rate of increase of failure and defines the failure pattern of the PoF function and is determined by the physical failure characteristics of the asset.

- **Decreasing Failure Rate**. An asset with early life failures or infant mortality should have a shape parameter in the range $(0 < \beta < 1)$
- **Constant Failure Rate**. Assets with a failure rate that isn't affected by the asset age or condition should have a $\beta = 1$. This includes most assisted failure modes.
- **Increasing Failure Rates**. Age related failure moves have a shape parameter in the range $1 < \beta < 4.5$. A shape parameter greater than 4.5 should only be used where it is supported by failure data.

Figure 12 - Impact on the PDF by varying the shape parameter β



Where Endeavour Energy does not have sufficient data to calculate the shape parameter, values used elsewhere in the industry will be used. The values provided in Table 12 are recommended default parameters where the failure pattern is known, and no other source is available. Otherwise, a default value of 3.6 should be used as this approximates the normal distribution used in the AER Repex model.

Table 12 - Recommended default shape parameters for β

Failure Pattern	Shape Parameter	Description
Infant Mortality	0.5	Early life failures that decrease over time
Random	1.0	Constant hazard rate over time
Slow Aging	1.5	The hazard rate increases less as time increases
Fast Aging	2.0	The hazard rate increases linearly over time
Predictable Life	4.5	Most failures occur around the same time

The impact of common shape parameters can be seen below in Figure 13 and Figure 14.

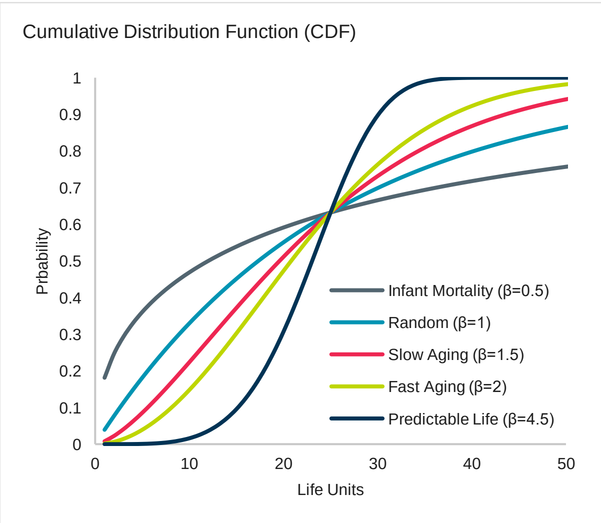


Figure 13 - Impact of shape on Weibull CDF

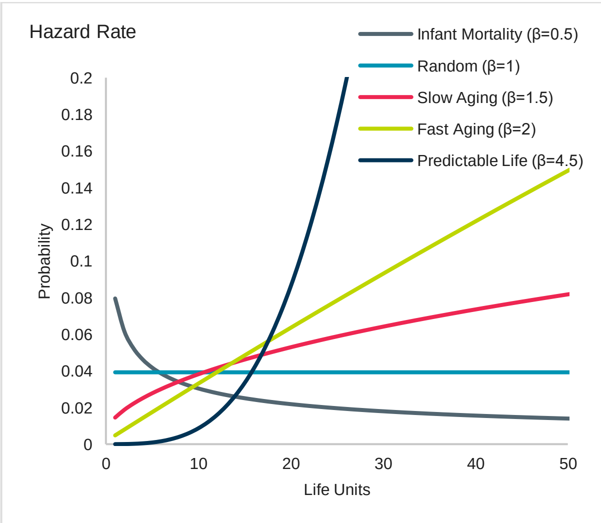


Figure 14 - Impact of shape on Weibull Hazard Rate

4.5.6.3 Scale Parameter

The scale parameter is the time when 63.2% of the assets will have been removed from service. Very few asset classes experience enough failures to set the scale parameter using this approach. Instead, the scale parameter is set based on the observed failure rate for the population of assets. The scale parameter should be adjusted until the number of failures predicted in a single year for the current population reflects the annual failure rate for the calibration period.

Due to the probabilistic nature of asset failures, the annual failure rate can vary from year to year. In these situations, consider using the average annual failure rate over a defined calibration period. Recommendation previous 3 to 5 years.

Limited Failure Data

Limited failure data is observed for populations that are very small, have a young average age relative to the true characteristic life or are subject to a very effective maintenance strategy. In these occasions a probability of functional failure will need to be estimated using other techniques.

- **External Experts**. Leverage any failure information gathered by industry groups or Original Equipment Manufacturers (OEM).
- **Rule of Three**. A conservative approach is to assume that three failures occur at the age of the oldest known suspended asset. (E.g., If the oldest asset in service is 80 years, three failures at 81 are added to the data set)
- **Zero Case Failure Test.** A method that infers the characteristic life required to observe zero failures over a period for a given population.

The zero fail tests case can be used if the asset experiences a constant failure rate by considering the likelihood of observing zero failures using the binomial distribution. Let:

$$C = Confidence$$
$$R = Reliability$$
$$N = Number\ of\ Test$$

Rearrange the binomial distribution to determine the confidence

$$N = \frac{\ln(1-C)}{\ln(R)}$$
$$R = e^{\frac{\ln(1-C)}{N}}$$

Assume constant failure rate and solve for MTTF:

$$R = \mathrm{e}^{-\frac{\mathrm{t}}{\mathrm{MTTF}}}$$
$$MTTF = -\frac{t}{\ln(R)}$$

Example

Consider 312 electronic devices aged 50 years that have exhibited 0 failures and we want to determine the MTTF with 95% confidence

$$R = e^{\frac{\ln(1-0.95)}{312}} = 99.04\%$$
$$MTTF = -\frac{50}{\ln(0.9904)} = 5183\ years$$

4.6 PoF derivations

Two variants of PoF curves are derived for each asset type. One is to assess the likelihood of a conditional failure and the second is to assess the likelihood that a functional failure may occur. Each PoF variant has a specific use, their definition and examples of uses are shown in Table 13 below.

Table 13 - PoF variants

PoF Variants	Description	PoF use
$PoF_{(Functional)}$	**Based on historical unassisted functional failure events.** The Weibull CDF parameters are estimated from asset data that is primarily based on historical unassisted functional failure events. This includes an asset that has catastrophically failed or had been partially operating in a degraded state but not be capable of delivering all its required functionality. There is some adjustment to the parameter estimation to allow for unaccounted censored data.	• Risk Calculations. • Proactive risk based targeted replacement forecast
$PoF_{(Conditional)}$	**Based on historical condition-based retirements** The Weibull CDF parameters are estimated based on historical condition-based replacements within the Endeavour Energy network. This is the probability that a defect is detected allowing for retirement to occur prior to any functional failure. This evaluation is observed in line with the current maintenance and inspection strategies.	• Reactive condition-based replacement forecast

This document is primarily focused on risk cost as a result of functional failure event occurring, so PoF refers to $PoF_{(Functional\ Failure)}$ unless stated otherwise.

4.7 Application of the Common Network Asset Indices Methodology (CNAIM)

The Common Network Asset Indices Methodology (CNAIM) methodology [2] is used in the United Kingdom to assess the failure probability of electrical network assets. In Endeavour Energy we have applied the CNAIM methodology to the power transformer asset class. The methodology develops a health score for each asset based on inputs of age adjusted for oil and signature test results, external condition of the transformer, loading history, design, and geographic location. From the health score, a probability of failure at the current time and a forecast of PoF into the future is resolved.

The CNAIM model applies caps (maximum values) and collars (minimum values) to the probability of failure curves for each asset and therefore provides a different PoF characteristic than provided by using a Weibull function to assess PoF.

The methodology also has provision for a number of inputs which allow the user to manually adjust the PoF of an asset based on observed condition or other factors which the subject matter experts believe are influencing its condition and reliability beyond that provided by the standard test results and other inputs.

The CNAIM model provides Health Score vs Age and PoF vs Health Score tables for each asset that provide the inputs used by the Copperleaf Predictive Analytics application to assess the optimum time for retirement and replacement intervention.

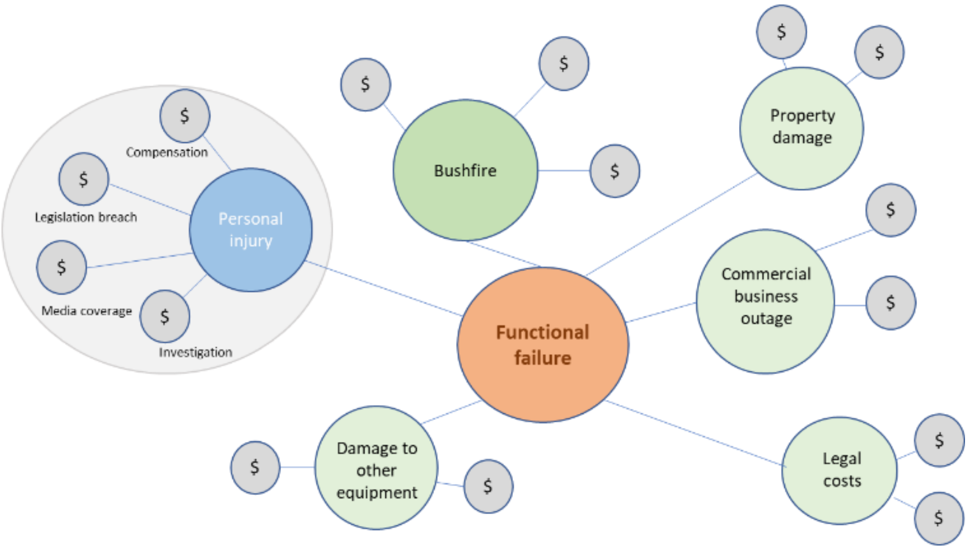
5. Consequence of Failure Model

The second key dimension of the asset risk methodology is the consideration of the consequence of an asset failure and its likelihood. This is used in combination with an assessment of the probability of asset failure to derive a single monetised risk-cost value for network risk.

Endeavour Energy's assets are located in many different locations in New South Wales across Sydney's Greater West, the Blue Mountains, Southern Highlands, the Illawarra, and the South Coast. These assets operate under a differing range of circumstances such as with heavy industrial, commercial, or residential area's or located in a busy shopping centre, school zones or bushfire prone land.

The Consequence of Failure (CoF) is a probabilistic model that converts the range of possible consequence outcomes after a functional failure occurs into this single monetised value. The CoF is determined for each failure with consideration made to various adverse effects as shown in Figure 15 below. Each of these effects has a subset of related consequences as illustrated for Personal Injury.

Figure 15 - Example of adverse effects that may result from a functional failure



Consequence events are typically selected and used as inputs to the model based on Endeavour Energy's own historical data from actual failure events.

This simplified CoF calculation can be shown in the equation:

$$CoF = \sum_{consequecne\ category}^{category} \left(\begin{array}{l} [Likelihood_{outcome\ 1} \times Consequence\ (\$)_{outcome\ 1}] \\ +[Likelihood_{outcome\ 2} \times Consequence\ (\$)_{outcome\ 2}] \\ + \qquad \vdots \qquad \times \qquad \vdots \\ +[Likelihood_{outcome\ N} \times Consequence\ (\$)_{outcome\ N}] \end{array} \right)$$

This CoF equation is applied to each nominated risk consequence to reflect the nature of different consequences arising from the failure of an asset. The total CoF for an asset, is the sum of all the different consequences assessed. To assist in this process, the model is developed using event tree analysis to visualise the events that can occur once a failure has been initiated. Each branch of the event tree requires:

- Likelihood of Consequence (LoC). The probability of that event (E.g., fire initiation) occurring given all the prior events on the tree have occurred; and
- Cost of Consequence (CoC). The termination of each branch is the cost of that event occurring (E.g., Cost of Major Bushfire) and aligns to consequence costs used across Endeavour Energy.

The calculation of the CoF is assessed on the same failure mode as the PoF.

5.1 CoF consequence categories

CoF consequence categories for use in the model are selected from a defined list of Value Measures as detailed in the company risk management procedure GRM0003. Each asset may encounter consequences associated with all or some of these Value Measures. This is to provide a consistent structured approach to risk consequence assessment.

These Value Measures are briefly outlined in Table 14 below.

Table 14 – CoF consequence categories

Value Measure	Description
Safety	Safety and health consequences to workers, public/consumers from an asset which results in a minor injury through to fatality. The consequence is typically expressed in terms of the Value of Statistical Life (VoSL)[13].
Reliability	Loss or interruption of network electricity supply as a result of a functionally failed asset resulting in an unplanned customer outage. The consequence is typically valued via Value of Customer Reliability (VCR)[14] to the consumer type affected by the supply interruption.
Legal/Compliance	This refers to costs associated with a legal or regulatory/legislative compliance breach arising from the failure of an asset.
Environmental	Loss to the natural environment surrounding ecology, flora, and fauna and also the clean-up remediation following the failure of an asset.
Bushfire	Property damage and loss from a bushfire event that was initially ignited following the failure of an asset.
Financial	Cost of replacement or repair of the asset including under emergency conditions, and the costs arising from damage caused to other assets. Also, any other related costs that are not considered in other value measure consequences.

5.2 Likelihood of consequence (LoC)

The LoC is the percentage probability that each asset failure results in a consequence occurring. Each asset class has an LoC parameter (often made up of multiple LoC values, for example weather and time of day) for each consequence type.

The LoC incorporates a range of information. This includes:

- The various failure modes that an asset may experience and the frequency with which each failure mode is expected to occur.
- The likelihood of a failure mode for the asset giving rise to a situation that could result in a risk if other criteria are met.

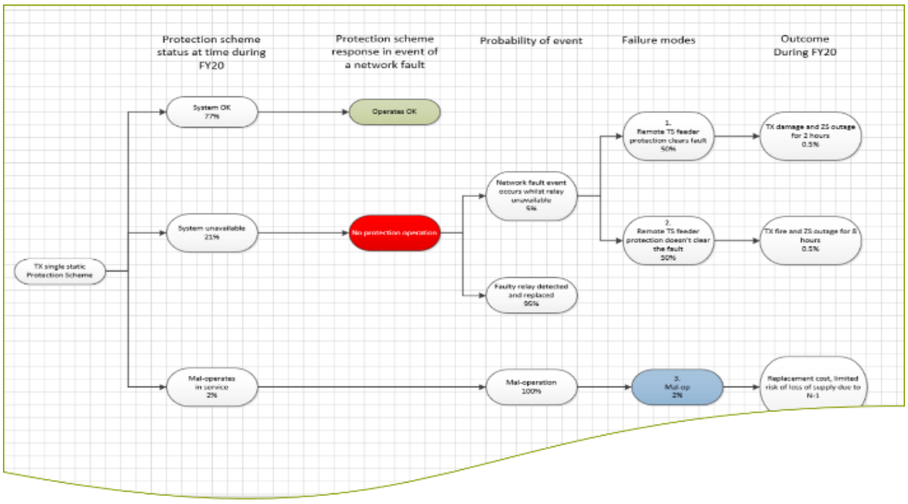
[13] In alignment with Australian Governments OBPR Value of statistical life.

[14] In alignment with the Australian Energy Regulator’s (AER) published Value of Customer Reliability (VCR) report.

- The likelihood of the other relevant criteria being met (such as the probability a member of the public is within the explosive radius of an asset that fails in an explosive manner or the probability of a fire occurring on a high fire danger day).
- The presence and capability of mitigating factors (such as blast walls for explosive safety risks or bunding for containing oil spills); and
- Other factors.

Where significant differences in the likelihood of a consequence occurring exist within an asset class, the LoC parameters may differ between individual assets and/or asset types. Documentation of the approaches to calculating LoC parameters for each asset class is covered in the relevant Asset Class Plans for each asset class and/or the risk model documentation.

Figure 16 - Example of a fault event tree to determine likelihood of failure events



5.3 Likelihood adjustments due to network configurations

5.3.1 Calculation of reliability risk in redundant systems

At the sub-transmission voltage levels there is generally a level of redundancy built into key elements of the network such that the loss of one element (such as a power transformer or a 33kV line) will not result in the loss of supply to customers. On this basis, the reliability risk associated with the functional failure of these assets is essentially nil. As the reliability risk is the key driver for planned risk-based replacement, generally the cost-benefit model will favour a run-to-failure approach for these assets. However, in practise there are a number of factors which impact the reliability performance of redundant systems:

- There is a probability that the alternate supply element will be out of service either for maintenance or due to a fault elsewhere in the network. (The standardised value of the likelihood of this occurring is 1%)[15]; and
- There is a probability that the alternate supply element will fail at the same time as the asset in question. This is particularly a risk for pairs of aged power transformers whereby the event which triggers the failure of one of the transformers may also trigger the failure of the other, or the failure of one may trigger the failure of the other.

[15] The probability of two assets being failed simultaneously can be calculated from multiplying together the Annual PoF x Outage duration (hours)/Hours pa for each asset together. This will typically give a likelihood of around 1 x10^{-6} or less, which is not material. The 1% value considers a range of factors including maintenance windows, failures of auto-changeover systems etc and is a generally accepted value. 1% LoC also yields values of reliability risk which are not material to the cost-benefit equation.

The asset classes whose reliability risk is most affected by redundancy in the network is power transformers (PX) and circuit breakers (CB).

Circuit breakers are more complex as they are switching elements, a catastrophic failure (such as a bushing failure) will cause the circuit breakers either side of this asset to operate, increasing the likelihood of causing a loss of supply. The failure may also physically impact on neighbouring switch bays (shards of porcelain bushing causing damage to adjacent switchgear bushings) further widening the extent of the outage. Therefore, the reliability risk impact of a circuit breaker failure is a function of the type of breaker (porcelain or polymeric bushings, oil or SF_6 or vacuum insulation), the topology of the substation (number of busbars and power transformers and whether or not there are bus-section circuit breakers installed), the actual breaker that fails (primary side feeder, primary side transformer, secondary side transformer, bus-section or secondary side feeder) and the protection and control routines set up for the substation.

The method used for estimating the reliability risk of power transformers is more straightforward and is summarised in Table 15 below. The second column shows the likelihood of the reliability impact occurring (LoC) while columns three – six show the proportion of the maximum cost of consequence (CoC) which is modelled as occurring based on the number of power transformers installed in the substation. The consequence is unserved energy the full value of which = substation maximum demand (MW) * load factor (% of maximum demand) * VCR ($/MWh) * outage duration (hr).

It is assuming that in a single transformer site there is nil redundancy and in each other substation there is a single transformer redundant which notionally provides an N-1 level of supply security.

Table 15 - Power transformer reliability risk estimation methodology

Reliability Risk Element	**LoC** (%)	**CoC** (% of maximum unserved energy)			
		Single transformer substation (no redundant transformer)	**Two transformer substation**	**Three transformer substation**	**Four transformer substation**
1. Principal failure impact	100	100	0	0	0
2. Redundant elements not being available	1	N/A	100	50	33
3. Simultaneous failure of redundant element	PoF of redundant element * Constant	N/A	100	50	33

The third reliability risk element, simultaneous failure of redundant element, has a material impact on both the reliability risk CoF as well as the financial risk CoF[16]. As this is an estimated value without a

[16] The financial risk is increased by the probability of having two transformers fail and their replacement needing to be funded.

substantive basis in historical data, a constant is included to allow the effect to be adjusted to achieve outcomes which appear to be reasonable and give consistent results across the asset class.

Where multiple transformers in a substation are of similar age and condition, they will be identified by the cost-benefit value assessment for replacement at the same time. The rule applied in this case is to schedule the transformer whose replacement gives the highest value for planned risk-based replacement and then to defer the second unit for reassessment prior to the next regulatory control period.

Given two transformers of advanced age, each with similar health scores, once one is replaced, the likelihood of the simultaneous failure reduces significantly and therefore the assessment being re-run for the next RCP may not recommend the risk-based replacement of the remaining aged transformer.

5.3.2 How risk for systems attached to a primary asset is calculated

A number of primary assets are controlled and/or protected by secondary protection and control systems and are supported by auxiliary systems. Power transformers are the most closely integrated with protection and control, with a range of protection systems and a control system to manage voltage regulation, cooling modes and automatic change-over to an alternative transformer after a failure. The capacity of the power transformer is also dependant on the correct functioning of its auxiliary cooling systems.

The associated protection and control and auxiliary systems can have a significant influence on the reliability of the primary asset. The strategy for managing these systems is that the associated protection and control systems are modelled and managed as secondary systems, but the auxiliary systems (in the case of power transformers) are modelled as part of the primary asset.

Note that auxiliary power supplies in zone and transmission substations have their own asset class and are therefore modelled as their own individual systems, including auxiliary transformer, cabling, and switchboard(s).

5.3.3 Non-independent failures

Some assets are part of integrated systems where their failure and subsequent replacement cannot be considered in isolation. A typical example of this is an oil-insulated circuit breaker[17] in a 33kV or an 11kV switchboard. The failure of any circuit breaker in these switchboards is likely to result in an explosion and oil fire, which if it does not destroy the entire switchboard immediately, will pollute the busbars with soot causing rapid corrosion and deterioration of insulation strength over time. Consequently, the entire switchboard will require replacement in the short-term after such an event.

In order to model this effect, switchboards comprised of oil insulated circuit breakers (and the early SF_6 switchboards) are modelled as single assets, with a PoF being an aggregation of the PoFs of each CB within the switchboard as well as that of the busbars themselves. Likewise, the consequences of failure include unserved energy from the complete loss of the supply from the section of board and/or substation for an extended period after failure and financial risk costs which include the complete replacement of the switchboard as well as substantial repairs to the control building.

[17] Early model SF6 insulated circuit breakers in switchboards did not have adequate air-tight isolation between chambers and busbars and therefore are usually damaged beyond viable long-term repair after the failure of any CB in the busbar.

5.4 Cost of consequence (CoC)

The CoC is the cost that will result from a given consequence occurring. Each consequence could result in a range of outcomes with varying levels of severity. The CoC must reflect this and ensure the value used is representative of the average consequence expected if a consequence does occur.

The CoC can be calculated from the range of possible consequence outcomes using the formula below:

$$Cost\ of\ Consequence_{consequence\ category} = \left(\begin{array}{l} [Likelihood_{outcome\ 1} \times Consequence\ (\$)_{outcome\ 1}] \\ +[Likelihood_{outcome\ 2} \times Consequence\ (\$)_{outcome\ 2}] \\ + \qquad \vdots \qquad \times \qquad \vdots \\ +[Likelihood_{outcome\ N} \times Consequence\ (\$)_{outcome\ N}] \end{array} \right)$$

The likelihood is the probability that the given consequence outcome will be observed following a failure. The likelihood that the failure results in no consequence is already accounted for in the LoC, so the likelihood values in the CoC formula must sum to at least 100% (every consequence event must cause at least one consequence outcome) and in most cases the sum is expected to be exactly 100%. This is because each consequence event will usually result in a single consequence.

In some situations, there may be scope for multiple consequences per event, depending on the definitions of outcomes used. An example is an explosion that causes injuries to two or more persons. Often, the probability of the second consequence is so low it will be will close to zero and can be ignored.

If the CoC is only based on the most severe consequence that could occur, then the LoC must be adjusted to also represent the likelihood that such a severe consequence occurs. This is to be avoided, as it means the model is no longer able to incorporate the value of minor or moderate consequence events. The probability of low severity consequences is often higher than the probability of the most severe consequences, such that even with the lower cost per consequence, the expected risk value across many failures may be higher for the less severe consequences.

The risk categories and consequences considered by the risk framework are presented in the table below:

Table 16 - Consequence categories and outcomes

Consequence Category	Description	Consequence outcomes included
Safety – Public & Worker	Defined and expressed in terms of the likelihood of injury or death to the public and/or workers. Uses the value of statistical life (VSL) in accordance with GNV1119 [1]	- Injury type o Minor injury (non-permanent) o Significant injury (non-permanent) o Minor Injury (permanent, not substantially life changing) o Serious Injury (permanent, life changing) o Fatality - Number of casualties - Disproportionate factor

Consequence Category	Description	Consequence outcomes included
Financial	Defined as typically the repair costs after a failure. Expressed as the direct financial costs for repairs, labour, dollars per day for a level of customer engagement and dollars per day for a level of media response. Also includes any other financial impacts of the failure not covered by other consequence categories.	- Repairs labour - Repairs (non-labour) - Customer engagement - Media response
Reliability	Defined as the loss of energy served to customers. It is expressed in terms of the value of customer reliability (VCR).[18] Values of VCR for specific locations in the network are available from Network Planning Manager.	- Value of unserved energy o Due to asset failure o Due to over demand
Bushfire	Defined as the safety, financial and environmental consequences of a bushfire started by a network asset. Consequences associated with a bushfire are excluded from the other consequence categories and included in this category because a dedicated model is used for bushfire modelling.	- Bushfire caused: o Land & Property damage o Injuries and fatalities(safety)
Legal / regulatory compliance	Defined as the limited situations where compliance is an actual economic driver for asset retirement and/or replacement. Expressed as dollars per breach or investigation type.	- Investigation - Safety legislation breach - Environmental legislation breach - NEM rules breach - Litigation
Environmental	Defined as events that have a material impact on the environment, typically bushfires and oil spills. Expressed as the combined value of consequence factors, dollars per unit of SF_6 and dollar outcome cost for bushfire risk per feeder involved.	- Land or water clean-up (low, medium, high & extreme) - Hazardous gas (SF_6)

[18] AER – Values of Customer Reliability. https://www.aer.gov.au/networks-pipelines/guidelines-schemes-models-reviews/values-of-customer-reliability

6. Investment Selection

This section covers how the model uses the risk / cost calculations to provide intervention recommendation(s) based on all known information for an asset.

The sections below cover:

- Investment evaluation
- Sensitivity analysis
- Treatment of reactive replacements
- Selection of credible network options

6.1 Investment Evaluation

The sections below cover two methodologies for determining whether an investment is worthwhile and justified from an economic perspective. The first is a hurdle rate method, which is simple to implement and computationally simple.

This method is preferred by the AER as it provides a quick check that proposed investment is efficient by pointing to the optimum time for investment. Given its simplicity however, it may not always give accurate results, particularly with assets with complex and interdependent failure modes.

The second is the Net Present Value (NPV) method which provides the NPV of investment over a range of years.

Both methods are used by Endeavour Energy in assessing the value of proposed investment.

6.1.1 Hurdle Rate Method

The hurdle rate method is a simple approach to assessing whether investments provide positive value and to demonstrate capital efficiency. It can also be used to rank competing investments by rearranging the calculation into a benefit-cost ratio. The term hurdle rate comes from the requirement for the benefit to exceed a hurdle, where the hurdle is determined by the cost of the investment.

With the hurdle rate method an investment is justified if the risk and other costs (such as opex) mitigated in the first year is greater than the cost of financing the investment for that year. This can be expressed as the following:

$\boldsymbol{Replace\ if}$:

$$Risk \times \left(PoF_{(Cond)existing} - PoF_{(Cond)new}\right) + \left(Opex_{existing} - Opex_{new}\right) > Investment \times WACC$$

When comparing investments that have different lifetimes, the formula can be expanded to consider the depreciation of the asset created by the investment. That is:

$\boldsymbol{Replace\ if}$:

$$Risk \times \left(PoF_{(Cond)existing} - PoF_{(Cond)new}\right) + \left(Opex_{existing} - Opex_{new}\right) > \frac{Investment \times WACC}{1 - (1 + WACC)^{-Investment\ Lifetime}}$$

The extended version is more appropriate when the service life of the replacement asset is short.

Endeavour Energy applies the second method as a general rule and assigns a reasonable average value equal with the expected life of the asset to the value of the investment lifetime.

Both variants can be converted into a Benefit-Cost Ratio (BCR) by dividing the left-hand side of the inequality by the right-hand side. A higher BCR is better, so projects that have a higher BCR should be selected over projects with a lower BCR (assuming both projects' BCRs are greater than 1.0). Projects with BCR's less than 1.0 should not proceed unless there are qualitative (not modelled) reasons that justify the projects.

Justification of the Hurdle Rate method

To follow good investment decision making practices, the timing of investments must be optimised. This requires each investment to be evaluated against the same investment made one or more periods later.

In the case of this model, which operates at an annual timescale, the optimal timing test is to determine if deferral of one year would be more beneficial than investment in the current year.

For asset replacement investments, the risk of the new asset is usually negligible in the first year and for a significant portion of the asset's lifetime. When comparing immediate investment versus deferral of one year, the risk of the replacement asset failing in year t+2 is effectively identical for both options and can therefore be ignored.

Over time the one-year difference in age of the replacement asset will result in a slightly higher risk (although a single year difference is never going to be large for most PoF functions), but these future values will be reduced by discounting to a present value, so the present value difference in the lifetime risk of the replacement assets will (usually) be very small.

Due to this, the only year where there is a significant difference in risk for the replaced asset is t+1, when the deferred option still has the existing (relatively poor condition) asset while the investment option has a new (good/perfect condition) asset. Therefore, only consideration of the first year is necessary to determine whether to invest.

This also applies on the cost side. The only cost incurred during the first year is the financing cost of the capital required for the investment. In the extended version of the formula, depreciation of the new asset is also included. The depreciation reflects that the new asset will eventually need to be replaced and this secondary replacement will be expected to occur one year earlier than if the initial replacement were deferred by one year[19].

In the next 'year' of the model forecast, deferral will be tested again. With enough years forecast, the model will eventually reach a point where investment is justified rather than deferring yet another year.

6.1.2 Net Present Value method (NPV)

Another approach is to calculate the NPV of the investment relative to a counterfactual case where no investment is made. In the model, the counterfactual is to not invest and allow the asset to fail and be replaced reactively.

The NPV approach used by Endeavour Energy assumes that no further investment is applied to the asset at any point in the future (excepting standard maintenance) once it is replaced. This means the replacement asset will remain in service until it fails. After failure the asset is removed from the calculation. Risk associated with future generations of the asset are not included in the NPV calculation.

The basis of this approach is that the purpose of the investment is to defer the eventual failure of the existing asset and the realisation of the risk associated with its failure (as well as to gain any other benefits such as reduced consequences of failure, reduced opex and better performance which may be provided by the modern equivalent replacement asset). An investment is economic if the deferral value is greater than the

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[19] Because of the significant uncertainty regarding the likely timing of the secondary replacement, some NSPs using the Hurdle Rate approach ignore the depreciation component. However, EE consider the depreciation component to reflect the real-world situation and use this approach, applying an average likely life to the investment lifetime value.

cost of the investment. The purpose is not to avoid risk, as this would require ongoing replacements of future generations of the asset into perpetuity or decommissioning the asset entirely, which is a highly uncertain proposition in terms of outcomes and beyond the scope of this model.

The total risk (excluding escalation and discounting) is the same (for a like-for-like replacement) irrespective of whether the investment is made or not as the asset is guaranteed to eventually fail given enough time. However, if the investment is made the risk will be incurred further into the future and with the effect of discounting this will provide a net present benefit to the participants in the electricity market[20].

The following terms are relevant to the NPV approach:

Current year: this is the point in time when the NPV calculation is being made for an asset. It is implied that the asset has survived until this point in time as the NPV calculation would otherwise not be required. The relative PoF values used in the calculation are always baselined to the current year.

Investment year: this is the year when the proposed investment is being tested to occur in. The investment year cannot be before the current year. In the no-investment case this is the year when the investment could have been made but was not.

Deferral period: this is the number of years between the current year and the investment year

Existing asset: the currently installed asset with no investments applied to it

New asset: the asset after an investment has been applied to it. This may be a brand-new asset if the investment is for a replacement.

Maximum asset lifetime: The number of years that it will take an asset's CDF to reach ~100% after the investment is made. In practice, CDF = 99% will give sufficiently accurate results.

Calculation horizon: typically set to 175years as this captures the life of our youngest assets plus the deferral of the replacement asset. the number of years of future values included in a single NPV calculation. As NPV represents values over time, a calculation horizon is required. To avoid the requirement for terminal values the calculation horizon is set at the maximum replacement asset lifetime (CDF ~ 100%) plus the deferral period. All values beyond this point in time are zero (hence a longer calculation horizon does not create more value) as the PoF is zero (the asset has already failed and been removed from the calculation).

Planning horizon: the number of years that investment decisions are being projected for. Each investment decision is summarised by an NPV. There are two variants of planning projections:

- **Conditional planning:** where in each NPV calculation the current year increases by one year until the current year equals the final year of the planning horizon. The deferral period is always zero in this calculation. Each planning year assumes that the asset did not fail during the preceding year (or any prior year).
- **Non-conditional planning**: where in each NPV calculation the deferral period increases by one year until the deferral period equals the planning horizon. This variant is required for identifying optimal investment timing and is used by Endeavour Energy.

[20] The AER requires investment to be seen through the prism of benefits to participants in the electricity market through for instance, reduced safety risks, reduced risk of loss of supply etc

6.1.2.1 NPV Calculation

The formula for calculating the NPV of an investment that is deferred by X years is:

$$NPV_X = \underbrace{\frac{-Investment + CoF_{existing} \times \sum_{t=1}^{H-X} \frac{PoF_{existing,t+X}}{(1+WACC)^t} - CoF_{new} \times \sum_{t=1}^{H-X} \frac{PoF_{new,t}}{(1+WACC)^t}}{(1+WACC)^X}}_{\text{Net benefit after investment}} \times \underbrace{\prod_{x=0}^{X} \left(1 - PoF_{existing,x}\right)}_{\text{Adjustment for probability of survival to investment year}}$$

Notes:

t is the number of years after the investment year
H is the calculation horizon. From the point when the investment occurs at $t = 0$ the remaining time horizon is $H - X$
For simplicity the formula excludes other benefits (such as opex savings)
$PoF_0 = 0\%$, i.e., the asset cannot fail before the current year. This ensures the final term is zero if the there is no deferral (the asset is replaced immediately).
The PoF terms used for the existing assets use a modified version of the ‘relative PoF’ which has been adjusted to ensure that the asset has not only survived to its current age, but also will survival to the proposed investment year. This is done because the entire term ‘Net benefit after investment’ (which includes investment cost and risk value) is multiplied by ‘Adjustment for probability of survival to investment year’. This probability of survival factor is only applicable for investment cost. Multiplying the ‘relative PoF if survives to investment year’ by the probability of survival simplifies to being the ‘relative PoF’ which is the correct PoF intended for this calculation.

The first part of the formula is the investment (negative as it is a cost) plus the value of risk deferral, all discounted by the number of years to when the investment would have occurred. The second term, which uses the product operator (capital pi symbol) is the probability the existing asset survived the deferral period to the year when the investment could be made. If the asset does not survive, the investment does not occur, and the risk deferral does not happen.

When there is no deferral period ($x = 0$) the denominator of the first term equals 1, the second term equals 1 and the third term equals zero, so the NPV is simply the numerator of the first term.

6.1.2.2 Investment Timing Using NPV

To understand how the risk / cost trade-offs change overtime and when an asset has / will change from being a NPV negative to a NPV positive investment the above calculation is done over an extended period (at present a 20-year window). The aim of this window is to understand when an intervention option changes from being NPV negative to positive, the rate of change from one year to the next and the point at which the NPV is at its maximum.

$$\boldsymbol{NPV\ Maximum} : NPV_t > NPV_{t+1}$$

The change in NPV is simply an extension of the hurdle rate method, with all future years up to the calculation horizon included rather than only the first year. The NPV method may produce a more accurate result if there is enough difference in the NPVs for the years after the first year. However, the hurdle rate is expected to produce an investment timing within 1-2 years of the true optimal investment timing in all but the most extreme circumstances or complex asset failure models.

This NPV calculation can be inserted into the investment decision rule as:

$$\frac{-Investment + Risk_{existing} \times \sum_{t=1}^{H-X} \frac{PoF_{existing,t+X}}{(1+WACC)^t} - \mathrm{Risk}_{\mathrm{new}} \times \sum_{t=1}^{H-X} \frac{PoF_{new,t}}{(1+WACC)^t}}{(1+WACC)^X} \times \prod_{x=0}^{X} \left(1 - PoF_{existing,x}\right) > \frac{-Investment + Risk_{existing} \times \sum_{t=2}^{H-X+1} \frac{PoF_{existing,t+X}}{(1+WACC)^t} - \mathrm{Risk}_{\mathrm{new}} \times \sum_{t=2}^{H-X+1} \frac{PoF_{new,t}}{(1+WACC)^t}}{(1+WACC)^{X+1}} \times \prod_{x=0}^{X+1} \left(1 - PoF_{existing,x}\right)$$

It is necessary for the decision rule calculation to use the non-conditional approach (which applies deferral rather than changing the current year) as the risk associated with failure during the year before investment on the right-hand side of the inequality must be included. This means the PoF is not re-baselined for the deferred NPV calculation.

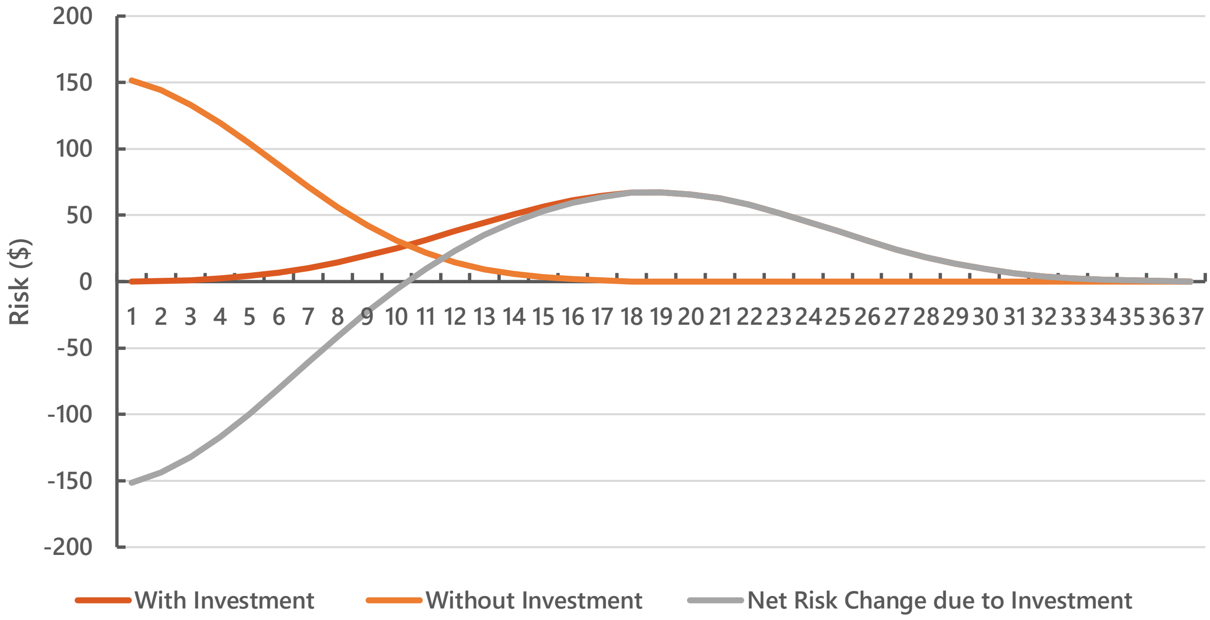
6.1.2.4 PoF and Risk Using NPV

The NPV calculations use the relative probability version of PoF (see Section 4.1). This is necessary because risk will fall when the asset is reactively replaced. For simplicity, the calculation used by Endeavour Energy assumes the asset can only fail and be reactively replaced once (unless the asset is repairable, in which case it can fail multiple times).

With this assumption, after several years the existing asset will have failed, and risk will fall to zero.

The figure below shows the risk profile with and without investment and the grey line is the net change in risk due to investment. Note that in later years the net risk is higher with investment. This is because the existing asset has already failed, and the risk associated with the secondary replacement is ignored (to simplify the model).

Figure 17 - Example Risk with and without Investment



Because of this implementation, the benefit of an investment is the deferral of risk rather than avoidance of risk. If the calculation horizon is shortened, the calculation of the NPV may exclude some or all of the periods where the grey line is above zero (representing a negative benefit), which would overstate the benefits provided by the investment. To avoid this, in the above example, the calculation horizon should extend to at least 37 years.

6.2 Sensitivity Analysis

The purpose of sensitivity analysis is to communicate the impact / uncertainty model inputs have on the confidence of the modelling results. The primary use case for sensitivity analysis is to:

- Determine whether an investment recommendation will change based on if the inputs differ from the expected value.
- Determine the impact an assumption has on outputs and assign a priority for replacing it with quantitative analysis where it is found to have a material impact on recommendations.

Sensitivity analysis is required because, while most calculations use a discrete value for each of the inputs, there is often a degree of uncertainty around the inputs. This can be caused by lack of confidence in an assumption, or because the input varies depending on circumstances that have not been modelled (E.g., replacement cost). At Endeavour Energy, most inputs are point estimates with the expectation of transitioning key inputs to ranges or distributions.

Table 17 - Sensitivity input types

Input Type	Example	Description
Point Estimate	10	A static input (usually an assumption) is adjusted by changing the variable by a fixed percentage based on the confidence in the input. At Endeavour we use +/- 3%, 5%, 10%, 20%, 50%
Range	8 – 12	Lower and upper limits are provided. The mean value is used for most calculations.
Distribution	Normal Distribution $(\mu = 10, \sigma = 1)$	A distribution representing the probability of the input being a value. The mean value is u

Endeavour Energy's approach to sensitivity analysis is to use extreme bounds analysis first and only use a Monte Carlo simulation where the recommendation is likely to change. Most models are dependent on many inputs, so a one at a time analysis is recommended to eliminate inputs and reduce the number of simulations required.

Table 18 - Sensitivity methods

Method	Sensitivity Method
Extreme Bounds Analysis	Provides the best-case and worse-case scenarios. All inputs are adjusted to find the extreme minimum and maximum values that can be observed for the modelled output: — Point Estimate. Adjust by a fixed percentage based on SME confidence in the output. — Range. The lower or upper limit that leads to the extreme value. — Distribution. The 95% confidence limits (i.e., two standard deviations from the mean)
One at a Time	One input is adjusted at a time. This can be useful for removing inputs that don't have a material impact on model results from further sensitivity analysis.
Monte Carlo Simulation	A model is developed to predict the probability of the output given the inputs. The Monte Carlo Simulation randomly samples a value for each of the input and calculates the output based on these inputs. This process is repeated until the range of outputs can be represented by a histogram.

The most practical application of sensitivity analysis is completing a sensitivity test for low-volume asset replacements where recommendations are made for individual projects. For high-volume assets, there is usually enough variation across the asset population to reduce the importance of sensitivity testing. While the individual assets selected for investment may be targeted for investment following more detailed analysis, the overall quantity of investments is likely to remain the same.

To manage complexity the tests should be limited to the parameters which have the most significant impact on the results. For many assets this will be the variables that make up the reliability benefit result including PoF, LoC and VCR.

Table 19 - Sensitivity tests for individual replacement projects

Sensitivity test	
Discount rate	The discount rate is the most common sensitivity test. However, for regulatory approval the WACC as approved by the AER is widely accepted as an appropriate input for the discount rate so there is a low level of uncertainty for this parameter.
Probability of failure function	The PoF Function can be adjusted to produce higher or lower PoF values or a steeper or flatter failure curve. As the shape parameter of a Weibull is the most uncertain of the three parameters changing it is generally the most appropriate test.
Replacement cost	Replacement cost is often highly uncertain (with estimates usually in the +-20% or greater range during early business case phases) and has a very direct effect on the justification of replacement.
VCR	High and low values for VCR are often applied as a sensitivity test in business cases. Unserved energy risks are often the single largest source of risk and in some cases are orders of magnitude greater than all other risks combined.
Likelihood of consequence	LoC values may be tested, although this introduces significant additional testing requirements. An alternative is to do a single high and low test where all LoC values are increased or decreased.

6.3 Reactive replacement

Some asset classes may be operated run-to-failure because the assets have a low risk, high intervention cost or cannot be reliably identified before failure. In asset classes where proactive investment does occur, not all assets may be caught before they fail.

The expected number of asset failures within an asset class is equal to the sum of the PoF across all assets in that asset class. The PoF of any assets proposed to be proactively replaced (e.g., have reached their maximum NPV) are removed from the calculation. This establishes the relationship between planned and reactive asset replacements and allows changes in the planned program to be modelled in the corresponding reactive forecasts.

Since it cannot be predicted which asset will reactively fail, the model currently assumes that failures occur in the units that have the highest PoF. This is an optimistic view of asset failures as it results in the greatest amount of risk being removed from the network, as the risk removed is equal to PoF times the average consequence value (assuming the new asset has zero or near zero PoF).

Asset Classes with >1 Expected Failures

For asset classes with high volumes of units and relatively high PoF values, the expected number of failures will be greater than 1 per annum. That allows assets to be treated as failed during the year. The standard approach used in the model is to treat the N highest PoF assets within an asset class as having failed during the year, where N is the sum of PoF for the asset class rounded to the nearest integer value. The actual and conditional age for these units are updated to zero years.

Asset Classes with <1 Expected Failures

The model will not apply failures to asset classes with less than 1 expected failures per annum. Asset classes where this occurs are usually significant assets, such as power transformers, which fail rarely but may have high consequences when they do fail.

Alternative approaches include:

- A probabilistic approach where a random number generator is used to determine if one asset fails. If the random number between zero and one is less than the sum of PoF for the asset class, the unit with the highest PoF is assumed to have failed and is replaced with a new asset.

- A cumulative approach where the highest PoF asset is assumed to have failed when the cumulative sum of PoF for the asset class reaches one. However, this is complicated by proactive replacements that may have removed the units that contributed to the sum of PoF in earlier years.

Repairable Asset Classes

Repairable asset classes are not changed after failure. Therefore, individual assets are not identified as failed in the model.

6.4 Credible options

When undertaking this cost benefit analysis, Endeavour Energy gives due consideration to what intervention options are available (inclusive of non-network options), before identifying the best way to address needs on the network through the application of the RIT-D process

The model can be used to assess any option so long as the impact of the option on the PoF of the asset can be estimated.

The typical types of options and PoF changes that can be applied are:

Table 20 - Common Investment Options

Option	PoF and other parameter adjustment approach
Non-network	New PoF function as appropriate for the non-network assets (if applicable)
Mitigation	Depends on mitigation options available. Likely to be no change in PoF but a reduction in the LoC or CoC.
De-rating	Depends on the unique situation and may or may not change the PoF. May also impact on LoC and CoC.

Option	PoF and other parameter adjustment approach
Refurbish	Revise the health index for the asset to reflect the improvement in condition. If all defects are repaired, then the health index should be set to the typical health index value for an asset of the same age. This approach depends on how the health index has been determined and/or how the PoF function has been implemented for the asset class.
Like-for-like replacement	Reset asset age/condition/health index to the value for a brand-new asset. Continue to use the same PoF function.
Replacement with different asset	Reset asset age/condition/health index to the value for a brand-new asset. Use the PoF function for the asset class of the new asset. If this doesn't exist, then develop a PoF function for the new asset class.
Retirement	PoF no longer applicable. May have impacts on LoC and CoC for other assets.

7. References

[1] "GNV1119 - Quantitative determination of reasonably practicable risk control measures when assessing health and safety risks, Am 1," 2022.

[2] "DNO Common Network Asset Indices Methodology. Health and Criticality - Version 2.0 Draft," UK Ofgem Safety, Resilience and Reliability Working Group, 2020.

[3] Endeavour Energy, "Company Procedure Governance - GRM 0003 Risk Management, Amendment 16," 2022.

[4] NSW Government, "Electricity Supply (Safety and Network Management) Regulation 2014 - NSW Legislation," 2014.

[5] Australian Energy Regulator, "Industry practice application note - Asset replacement planning," AER, January 2019.

[6] Endeavour Energy, "Winter Demand Forecast 2021 - 2030," Network Demand Forecasting Section, 2021.

Appendix 1 – Probability of Failure Functions

Probability Distribution	Description	Parameterisation Approaches
Uniform	Constant failure rate. Rarely used as most assets exhibit degradation over time. Is sometimes used for assets with unknown condition and are unlikely to be proactively replaced but require a PoF to ensure some reactive costs are included in the forecast. Has been observed for back-up batteries, some minor IT equipment and for balance-of-costs for asset classes that would otherwise go unmodelled.	PoF=Expected number of failures p.a./number of units
Linear	Failure rate increases steadily over time. Uncommon, could be used for less significant assets with short lives. Maybe some IT equipment.	Calculate PoF for age ranges and use linear regression to calculate a generalised PoF function.
Normal/Log-Normal	Failure rate increases exponentially over time. Used in the AER Repex Model. Some NSPs use this on the basis of alignment to the AER's model. It can also be justified where there is insufficient data to prove that other distributions are more accurate. The normal distribution is more common than log-normal, although care has to be taken to ensure the probability of failure before age zero is minimised (normal does not have a lower bound at zero)	The simple approach is to set the standard deviation at SQRT(mean) and back-solve for a mean that results in a reasonable number of failures.
Weibull	Failure rate behaviour over time can be flexibly adjusted to fit the data. Broadly used both domestically and internationally. The Weibull distribution can approximate other distributions by changing the shape parameter, including normal (3.6), log-normal (2.5), Rayleigh (2) and exponential (1). Typically set so that failure rate increases exponentially over time (shape > 2). Networks find setting parameters difficult, and results can be unrealistic using theoretically correct or data backed approaches. Typically, a back-solving approach is required.	There are various methodologies proposed for setting Weibull parameters in the literature, but the unique situation of electrical utilities mean most of these are not easily implementable. A more typical approach is to select a **shape** parameter, often based on an external source but sometimes from network failure data, and then back-solve for a **scale** parameter that avoids a step-change in predicted failures. A **location** parameter may also be used. Our approach has been to set the shift at the lowest observed failure age.
Cubic	Popularised by the EA Tech CBRM model, applies a cubic (third-order polynomial) formula to a health index, rather than age. The health index is calculated separately based on age and condition data. NSPs are moving away from this approach, but the Health Index approach does solve some definitional issues	One parameter is set to achieve a pre-determined relative PoF between two health index values. The second parameter is calibrated to the total number of failures observed over a recent comparable period.
Bathtub/Multi-distribution approach	Talked about in all the literature but never observed in practice. Introduces conflicts as the 'new' asset is no longer near risk-free. Requires an NPV approach with a reasonably long-time horizon to incorporate the low-risk segment of the asset lifecycle. Breaks the hurdle approach as the first-year risk is high, so the replacement is more difficult to justify. Some asset managers argue the bathtub doesn't exist in practice; the early failures are caused by specific manufacturer defects that are better modelled by separating affected assets into a separate sub-asset class	Separately calculate distributions for early, mid, and late life. Cut-off points should be selected to minimise steps when the PoF transitions from one phase to the next.

Appendix 2 – Non-repairable asset investment tool

Working template file showing an example the economic evaluation process for a non-repairable asset

ARM – Non-Repairable Assets r1.0.xlsx

Appendix 3 – Repairable asset investment tool

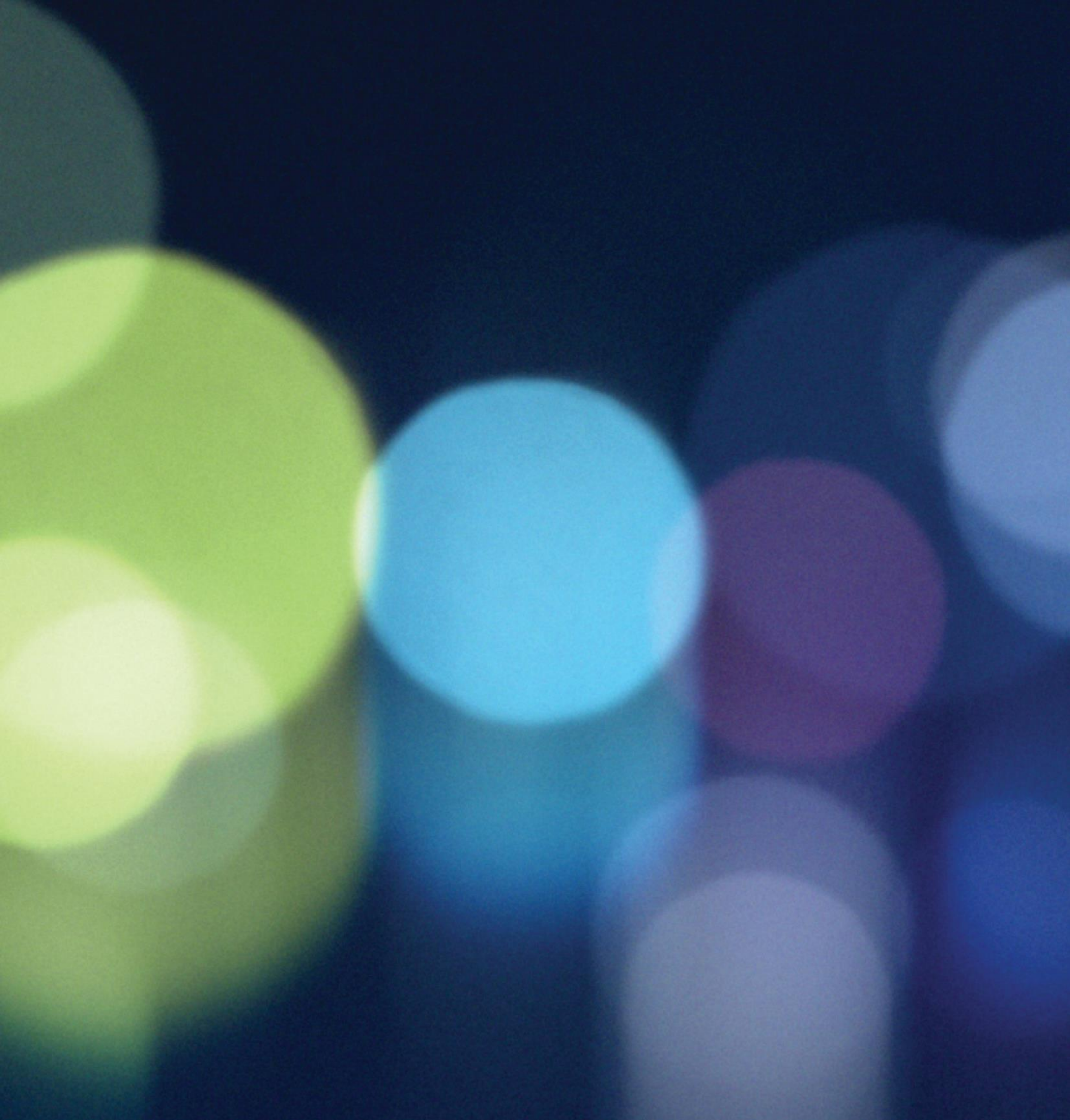
Working template file showing an example of the economic evaluation process for a repairable asset

ARM – Non-Repairable Assets r1.0.xlsx

Appendix 4 – Weibull parameter estimation tool

Working template of the Weibull parameter estimation tool.

Weibull_Curve_Generator r1.0.xlsx



Produced by Asset Planning and Performance Branch

W Endeavourenergy.com.au
E news@endeavourenergy.com.au
T 131 081

ABN 11 247 365 823