Asset Risk Quantification Guide

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Table of Contents

Approval and Amendment Record ... 2
Table of Contents ... 3
List of Figures ... 5
List of Tables ... 5
1. Purpose ... 6
2. Scope ... 6
3. Objective ... 6
4. Asset Management Definitions ... 7
4.1. Definitions ... 7
4.2. Definitions (Mathematical Symbols) ... 8
5. Risk Quantification ... 9
5.1. Assets versus Systems ... 10
5.2. Capex, Opex and Risk Weightings ... 10
6. Risk Quantification - Likelihood of Event ... 12
6.1. Failure Rate ... 12
6.2. Multiple Failure Modes ... 13
6.3. Probability of Failure ... 13
6.3.1. Weibull Analysis ... 13
6.3.2. Hazard Function ... 14
6.4. Joint Probability ... 14
6.5. Conditional Probability ... 15
6.5.1. Preferred methods ... 15
6.5.2. Conditional Probability of Failure expressions ... 16
7. Risk Quantification – Consequence of Event ... 17
7.1. Energy at risk ... 17
7.1.1. Interpreting energy at risk ... 17
7.1.2. Value of customer reliability (VCR) ... 18
7.1.3. Value of expected energy at risk ... 18
7.1.4. Zone Substation Failures ... 19
7.1.5. Distribution Network Feeder Failures ... 19
7.2. Safety Consequence ... 20
7.2.1. Likelihood of Consequence ... 20
7.2.2. Cost of Consequence ... 20
7.3. Bushfire Consequence ... 20

7.4. Environmental Consequence ... 20
7.5. Failure / Replacement Costs ... 20
8. Distribution Assets: Life Cycle Costing ... 21
8.1. Abbreviations ... 21
8.2. Life Cycle Costing - Overview ... 21
8.3. Acquisition (LCCA) ... 22
8.3.1. Distribution assets ... 22
8.3.2. Zone Substation Assets ... 22
8.4. Operating and Maintaining (LCCO) ... 23
8.4.1. Maintenance (CY) ... 23
8.4.2. Operation (CO) ... 23
8.5. Disposal (LCCD) ... 23
8.6. Worked Example: LV Overhead Services ... 24
9. Option Analysis ... 25
9.1. Typical Standalone Asset Options ... 25
9.1.1. Status Quo ... 25
9.1.2. Changing the existing Assets ... 25
9.1.3. System-related Options ... 25
9.1.4. Non-network Options ... 25
9.2. System - related Options ... 26
9.3. Risk Reduction ... 26
9.4. Worked Example: LV Services ... 27
9.5. Worked Example: ZSS Transformer Replacement ... 27
10. Sensitivity Analysis ... 29
11. Asset Performance ... 30
12. References ... 31
13. Appendix A – Asset Function Definitions ... 32
14. Appendix B – Probability and Consequence Tables ... 37
14.1. Probability of Consequence – Safety – All Assets ... 37
14.2. Distribution Asset Failure Rates ... 38
14.3. Zone Substation and Sub-Transmission Asset Failure Rates ... 43
14.4. Zone Substation Secondary Asset Failures ... 46
14.5. ZSS Building and Grounds Failures ... 47

List of Figures

Figure 5.1 Failure Mode Tree........ 9
Figure 7.1 Relationship between N, N-1 rating and energy at risk........ 17

List of Tables

Table 4.1 – Definitions........ 7
Table 4.2 – Definitions (Mathematical Symbols and Abbreviations)........ 8
Table 5.1 – Asset Classifications........ 10
Table 5.2 – Risk weighting factors........ 11
Table 6.1 – Selection of Likelihood Assessment method........ 12
Table 6.2 – Failure Expressions for parallel systems [11]........ 16
Table 6.3 – Q-values........ 16
Table 7.1 Risk weightings - Energy........ 17
Table 7.2 Values of customer reliability........ 18
Table 7.3 Average utilization factors........ 19
Table 8.1 – LCC Abbreviations........ 21
Table 8.2 – Investment and Maintenance Cost Elements........ 22
Table 8.3 – Maintenance Cost Elements........ 23
Table 9.1 – ZSS Transformer Option comparison total cost........ 28
Table 10.1 –Asset Sensitivity parameters........ 29
Table 13.1 – Asset Function Definitions........ 32
Table 14.1 – Probability of Consequence (Safety) [2]........ 37
Table 14.2 - Safety Consequence Costs........ 38
Table 14.3 – Distribution Asset Failure Rates........ 40
Table 14.4 – Distribution Asset Consequences........ 41
Table 14.5 – LV Service Failure Rates........ 42
Table 14.6 – LV Service Consequences........ 42
Table 14.7 – Zone Substation Asset Failure Rates........ 43
Table 14.8 – Zone Substation Asset Failure Consequences........ 44
Table 14.9 – Standard β-values (MGL)........ 45
Table 14.10 –Secondary Asset Failure Rates........ 46
Table 14.11 –Secondary Asset Consequences........ 46
Table 14.12 – Building and Grounds Asset Failure Rates........ 47
Table 14.13 – Building and Grounds Consequences........ 47

1. Purpose

The purpose of this document is to provide United Energy employees a reference guide of analytical methods and data to:

- Assess asset failure modes and their consequences;
- Determine probabilities of failure;
- Quantify varying types of asset risk and;
- Determine the least-cost approach.

for assets owned and operated by United Energy.

The document shall ensure a consistent approach to the assessment of different management options across different asset types, with a view to providing a consistent input for risk analysis purposes, as well as means of deriving relevant asset-related measures that can be used by the wider business.

2. Scope

This document covers the following areas of the asset life cycle;

- Asset dependability measure definitions
- Evaluating asset dependability measures (including reliability, availability, and failure rates)
- Performing failure analysis and determination of failure rates
- Assessing probability of failure of an asset
- Spares requirements analysis
- Life Cycle Costing
- Asset KPI development

3. Objective

The objective of this manual is to provide a body of knowledge to Asset Management engineers on appropriate methods to managing assets within United Energy asset management across the asset life cycle, that reflect industry best practice and the expectations of internal and external stakeholders.

This document shall be reviewed regularly and amended as required in order to reflect changes in relevant standards, the application of new technologies and methods, changes to network objectives and other drivers.

This document is a living document, and shall contain input data and methods based on knowledge at the time.

Any departure from this manual shall be approved by the United Energy Primary Assets team.

4. Asset Management Definitions

4.1. Definitions

The following series of definitions are recommended to be understood and referenced within Asset Management. All definitions are based on relevant standards. Where a source is not quoted, the definition will have been reworded from the relevant standard, but is consistent with the principle and relevant mathematical expression for the term.

Source	Term	Definition
AS ISO 55000.1	Asset	An item, thing or entity that has potential or actual value to an organisation
	Item	An individual article or unit
	System	A set of things working together as parts
IEC	(Required) Function	function considered necessary to fulfil a given requirement
	Reliability	The ability of an item to perform a required function under given conditions for a given time interval
	Maintainability	The ability of an item, under stated conditions of use, to be retained in, or restored to, a state in which it can perform its required function(s)
	Availability	The probability that a system is available for use at a given time
AS IEC 60300.3.3	Life Cycle	The time interval between a product's conception and disposal
	Defect	An observed condition that has not resulted in a failure, but will eventually result in failure
IEC 60050	Failure (of an item)	Loss of ability to perform the required function(s).
AS IEC 60300.3.3	(constant) Failure Rate	The rate at which failures occur
AS/NZS IEC 62740	Cause[1]	Circumstance or set of circumstances that leads to failure or success
AS/NZS IEC 62740	Human error	Discrepancy between the human action taken or omitted, and that intended or required

Table 4.1 – Definitions

Numerous industry groups may have subtle variations of the above definitions that generally reflect the interest or purpose of that body. The definitions in Table 4.1 serve as the most abstract, high-level definition that shall be used within Asset Management, and are derived from relevant standards and engineering literature.

Appendix A includes a list of UE network assets functional and failure definitions.

[1] A cause may originate during specification, design, manufacture, installation, operation or maintenance.

4.2. Definitions (Mathematical Symbols)

The following symbols and terms are recommended to be applied within UE asset management. The majority of symbols and terms are defined in IEC 61703.

Symbol / Term	Definition / Formula	Notes
λ	Failure Rate	
β	Common-cause factor.	$0 < \beta \leq 1$
α,β	Weibull distribution parameters	
μ	Poisson distribution parameter	
VCR	Value of Customer Reliability	Refer https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Value-of-Customer-Reliability-review
WACC	Weighted average cost of capital	The real discount rate that should be used in net present value calculations
f(t)	Probability density function	Refer IEC 61703 Table B.1
F(t)	Cumulative probability density function	
R(t)	Survivor function	
h(t)	Hazard Function	

Table 4.2 – Definitions (Mathematical Symbols and Abbreviations)

5. Risk Quantification

This section is intended to serve as a guide to asset managers on quantification of risks associated with assets in a structured manner.

For the purposes of this document, risk is defined as:

'the effect of uncertainty on objectives'

The focus of risk in this document is on uncertain events relating to asset in a given time period (typically one year)[2]. Each identified risk (there can be many risks associated with one asset) has a likelihood and a consequence.

Classifications of risk are included in three groups to align assessment with asset failure modes and effects as per Reliability-Centred Maintenance. This is summarised below in Figure 5.1 .

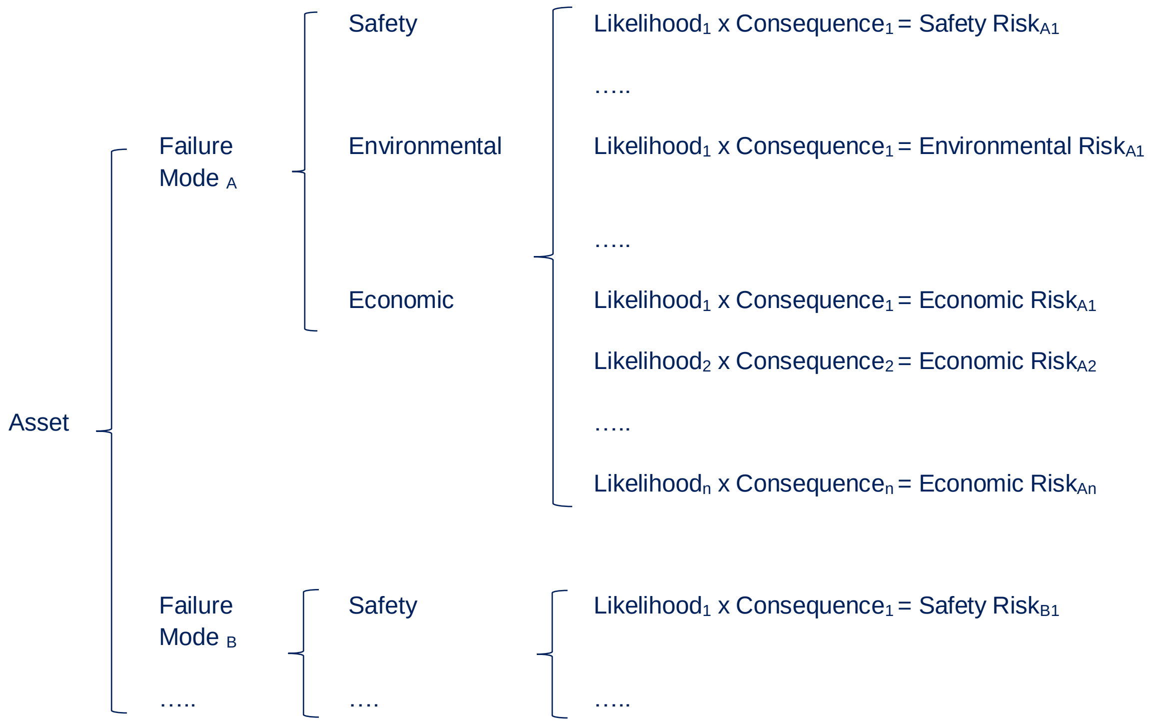

Figure 5.1 Failure Mode Tree

For each asset, different failure modes may exist, each with different consequences and likelihoods. Different failure modes and consequences can assist in the development of a total listing of asset risks. Failure modes are generally linked to the equipment's physical attributes and construction. Each failure mode has a likelihood, however depending on circumstances at the time, that failure mode may result in a variety of consequences.

[2] It is important to note the time period over which the risk is assessed.

The total risk can then be quantified as the sum of risks for a given time period. This can be expressed as:

$$Risk(t) = \sum_{n=1}^{n} h_n(t).PoC_n.CoF_n$$

Where:

n = number of failure modes

t = time period under analysis (typically a given year)

h(t) = hazard function, or probability of a failure (or failure mode if more than one failure type is under analysis) in time period under analysis (t)

PoC_i = conditional probability of a specific consequence occurring for a given failure mode.

CoF_n = Consequence Cost for a given failure mode.

5.1. Assets versus Systems

In the UE framework, Asset Life Cycle Strategy documents typically cover a single class of plant, such as a transformer or pole. However, these items on their own are not inherently useful; they only operate in conjunction with other items.

The collection of items into aggregates are generally studied as 'systems' – collections of assets. Systems are generally covered under 'non-asset class strategies', however for some redundant assets (e.g. zone substation assets), system analysis can be included in an Asset Life Cycle Strategy.

An example of major asset classifications is included below.

Term	Classification
Transformer	Item
Pole	Item
Feeder	System
Substation	System

Table 5.1 – Asset Classifications

Example: A pole is defined as an asset within the organization. The failure rate attributed to a pole is comprised only of failure modes related to poles. A distribution feeder in its' simplest form is a collection of poles, conductors cross-arms and transformers; its failure rate is comprised of failure modes relating to all items within the system. These items are generally connected in series, such that the failure rates are additive.

Example: A transformer is defined as an asset within the organization. A substation comprises a collection of transformers, buswork, switchgear and electronic monitoring systems; its failure rate is comprised of failure modes relating to all items within the substation (system). These items are connected in both series and parallel.

5.2. Capex, Opex and Risk Weightings

The following table demonstrates the relative weightings of types of valuation (either expenditure or risk). All risks are treated equally (proportionate), except for safety risk, for which a disproportionate factor is applied.

Cost type	Weighting factor
Capex	1
Opex	1
Risk – Safety (Disproportionate Factors)	10 for Bushfire risk in BCA areas 6 for bushfire risk in REFCL declared areas 3 for bushfire risk in HBRA areas 1 for bushfire risk in LBRA areas 3 for public safety risk for death and permanent disability 3 for worker safety risk for death and permanent disability 6 for multiple public or worker safety risk for death and permanent disability
Risk – Environmental	1
Risk – Energy & Other	1

Table 5.2 – Risk weighting factors

6. Risk Quantification - Likelihood of Event

The following table demonstrates which method should be applied to different asset types. The methods start off for the simplest approach, and increase in complexity

Assessment type	Complexity	When applied
Failure rate	Low	High-volume assets (or for single assets where a time-based failure curve is not possible)
Probability of Failure function	Medium	Single high-value or critical assets
Joint Probability	Medium	For substation assets with redundancy (e.g. two-transformer zone substation)
Conditional probability	High	For substation assets with redundancy where common cause failure(s) has been observed for the particular asset type

Table 6.1 – Selection of Likelihood Assessment method

6.1. Failure Rate

The discussion around asset failures and failure rates is the inverse to reliability; where an asset is 100% reliable, no failures will occur. Where an asset has a level of reliability less than 100%, the failure rate represents the difference between actual performance, and full reliability.

Failure rate defines the quantity of asset failures over a given unit measure (usually time, but sometimes there is another measure e.g. kilometers). For asset management purposes, in most cases given unit measures shall be per annum.

The failure rate shall be denoted using the Greek letter λ.

It is important to note that the failure rate of the asset population will change over time as the age profile of the asset base alters. As such, it is appropriate to perform an analysis of the expected number of failures for a given time t for the asset. This will result in a predicted change in the value of λ over time. It may prove useful to add a subscript e.g. λ_{2018} denotes the failure rate expected in 2018.

The failure rate can also change when the management techniques applied change.

Note that λ does not give the probability of failure of a specific asset, only the expected number of failures over a given time period for a group of assets. For the probability of failure of an individual asset, refer to the Hazard function.

Example: UE has 1500 RM6 switches in service, and experience an average of one in-service failure per annum – a failure rate of 0.00067 per year. Because failure rates on a per-asset basis are often very low, failure rates should be expressed as a higher number, typically per-thousand assets, or per-hundred kilometers.

$$\lambda_{RMU} = \frac{1}{1500} \times 1000 = 0.67\ failures/1000\ switches\ /\ year$$

If the number of RMUs installed increases to 3000, the number of failures can be expected to increase to 2 per annum, where λ remains constant.

If there is no data or evidence relating to the change in probability of failure of an asset over time, then the failure rate shall be assumed to be constant. In this case, the probability of failure of an asset shall be given as:

$$\text{PoF} = \lambda \,/\, \text{failure rate units}$$

This is simply the conversion of a failure rate per quantity of assets, into the failure rate for a single asset.

Example: UE has 1500 RM6 switches in service, with a failure rate λ = 0.67 /1000 switches/year. The PoF of a single switch = 0.67 / 1000 = 0.0007 per annum.

In many cases, prudent risk management techniques applied to assets have prevented failures from occurring, thus preventing the determination of failure rates (likelihoods) from being quantified. In such cases, expert judgement should be applied, considering learnings and experience from other asset operators.

6.2. Multiple Failure Modes

For a given asset, a single failure rate may be sufficient for simplistic asset analysis purposes. However, for assets with a number of failures, it is better to define the failure rate as a result of each failure mode. Different condition assessment techniques or engineering changes only affect specific failure modes, so it is prudent to understand the effect on the overall failure rate.

This method should only be applied if there is reasonable data to quantify the likelihood of different failure modes, for example, categorisation of internal failure data by cause type or by component. If this is not available, relevant industry data can be used.

Example: UE has a total of 365,000 services, with an average of 1900 failures per annum. Of these failures, 400 failures are attributed to vegetation-related causes, 20 vehicle impacts, and the remainder are electrical or mechanical failure. The overall asset failure rate can be expressed as:

$$\lambda_{total} = \frac{1900}{365{,}000} \times 1000 = 5.2\ failures/1000\ services\ /\ year$$

Failure rates by failure mode can be determined by:

$$\lambda_{vegetation} = \frac{400}{365{,}000} \times 1000 = 1.1\ failures/1000\ services\ /\ year$$

$$\lambda_{vehicle} = \frac{20}{365{,}000} \times 1000 = 0.05\ failures/1000\ services\ /\ year$$

$$\lambda_{elec/mech} = \frac{1480}{365{,}000} \times 1000 = 4.05\ failures/1000\ services\ /\ year$$

Logically, the sum of all failure modes is the overall asset failure rate: 1.1 + 0.05 + 4.05 = 5.2 failures / 1000 assets / year.

Breakdown of asset failures by failure modes is useful to refine the overall asset risk cost, as different failure modes have different levels of consequence.

6.3. Probability of Failure

6.3.1. Weibull Analysis

When modelling the behaviour of a specific asset over time, Weibull analysis may be used to determine the change in failure risk over time (if a change exists).

Weibull analysis should be conducted based on the principles of IEC 61649. The Weibull analysis should be a two-parameter model.

Where there are a number of assets still in service beyond the average failure age, or the asset replacements are driven by a mixture of asset replacements and failures, asset replacements should be treated as a suspension. Refer to IEC 61649 7.2.3.

Caution should be exercised when performing an analysis on the need to asset replacement which forecasts the average time to reach the asset reaching condition thresholds requiring preventative replacement. If the condition thresholds change, then a revised analysis will be required, as the time until the new condition threshold is met may be different.

It is recommended that where comprehensive asset data is available, the log-rank method produces reasonably accurate results. Where only partial data is available (e.g. for a certain time period), a non-parametric method (e.g. Kaplan-Meier) produces results that better match experience.

When using the Kaplan-Meier graphical approach, consideration should be given to fitting a number of different distributions to the plot to determine if a Weibull distribution matches the observation plot, or another distribution (e.g. log-linear) provides a better fit.

6.3.2. Hazard Function

The hazard function refers to the probability of failure of an individual asset at a given point in time and is calculated from the Weibull distribution.

It is defined as:

$$h(t) = \frac{f(t)}{1 - F(t)}$$

Where f(t) is the probability density function for the asset , and F(t) is the cumulative density function.

The hazard function shall be used where a Weibull distribution is able to be derived for an asset class or failure mode. This can be determined via:

- Calculation i.e. using log-rank method
- Calculation using other methods i.e. using a Mean-life Estimator such as Kaplan Meier
- Estimation i.e. deriving task effectiveness

The calculation of the Weibull function should be performed in accordance with IEC 61649. Assets still in service and assets that have been replaced should be considered as censored data when deriving the hazard function for functional failures unless there is clear evidence that a failure was imminent.

The outputs of any calculation or estimation should be checked for validity by comparing the number of failures expected by the hazard function (by multiplying the function with the asset age profile) to the actual observed failure rate for the asset (if available). Data quality issues may impact the quality of the result.

6.4. Joint Probability

For key electrical assets which have a significant (widespread) impact in the event of a failure, redundancy measures are often employed. For example, key protection and monitoring systems are often duplicated; substation transformers often have a level of redundancy or capacity margin during normal operating loads.

For these assets in the event of a single failure, it is unlikely that supply is lost for extended periods. However, multiple asset failures or increases in load beyond the redundant rating will result in widespread outages and customer impact.

For two plant in parallel, A and B, the probability of failure of either A or B = Pr(A) + Pr(B).

Where multiple failures are independent events, Pr (AB) = Pr (A).Pr (B)

Because of the variable nature in electrical load, the level of redundancy necessary to operate varies with time; for example, during winter, a three-transformer substation may be able to operate with only a single transformer online; as the load increases, two transformers may be necessary to supply load; during peak periods, the total station load may require all transformers in service, meaning for that period, there is no system redundancy.

As probabilities of failure are typically quoted on an annual basis, but restoration time typically occurs within one year (ranging from weeks to months for larger assets), care should be taken when analyzing joint probability risk as the failures will need to overlap within the repair period for some failure consequences (e.g. supply risk of a substation operating below N-1 levels). This can be done by reducing the failure rate by a factor proportionate to the restoration time of the asset [1].

6.5. Conditional Probability

In redundant systems, multiple plant failures may occur, rendering desired redundancy ineffective as a result of a shared cause or issue, rather than two separate events.

Where dependent or conditional events exist, Pr (AB) > Pr (A).Pr (B).

There is a large number of engineering references that indicate despite best practices, some level of dependency exists; that is, a conditional failure may occur. This may be caused by common elements to both assets, including similarities of:

- Design & construction (typically latent defects)
- Maintenance practices
- Operating duty
- Age/Condition
- Geography

The likelihood of a conditional failure depends on the engineering practices employed and experience. In order to comprehensively assess risk, it is recommended these risks are understood.

For the purposes of this section, the terminology 'common-cause failure' shall be used, where two or more component faults occur at the same time or within a short time period, with the same underlying cause.

6.5.1. Preferred methods

The beta-factor model is an extension of the joint probability assessment (outlined in 6.4), applicable to two-asset systems (such as a two-transformer zone substation).

The Multiple Greek Letter (MGL) method is the extension of the beta-factor model for 3+ asset systems.

The preferred methods to assess the likelihood of a common-cause failures is the Multiple Greek Letter model. This is one of the most commonly used Common-cause failure (CCF) models (the model simplifies to the β-factor model in the 2-asset case).

The general case for the MGL is shown below. For further information, refer to [11].

$$Q_k^{(m)} = \frac{1}{\binom{m-1}{k-1}} \left(\prod_{i=1}^{k} \rho_t \right) (1 - \rho_{k+1}) Q_t$$

Where $\rho_1 = 1$, $\rho_2 = \beta$, $\rho_3 = \Upsilon$, $\rho_4 = \delta$, $\rho_5 = \varepsilon, \ldots, \rho_{m+1} = 0$

6.5.2. Conditional Probability of Failure expressions

The following expressions shall be used to determine the probability of event for different substation parallel arrangements.

Substation Layout	Scenario	MooN State	Expression
Two-asset substation; all units operating in parallel	One out of two fails	1oo2	$2Q_1 + Q_2$
	Two out of two fail	0oo2	$Q_1^2 + Q_2$
Three-asset substation; all units operating in parallel	One out of three fails	2oo3	$3Q_1+3Q_2+Q_3$
	Two out of three fail	1oo3	$3Q_1^2+3Q_2+Q_3$
	Three out of three fail	0oo3	$Q_1^3+3Q_1Q_2+Q_3$
Four-asset substation; all units operating in parallel	One out of four fails	3oo4	$4Q_1+6Q_2+4Q_3+Q_4$
	Two out of four fail	2oo4	$6Q_1^2+6Q_2+4Q_3+Q_4$
	Three out of four fail	1oo4	$4Q_1^3+12Q_1Q_2+3Q_2^2+4Q_3+Q_4$
	Four out of four fail;	0oo4	$Q_1^4+3Q_2^2+4Q_1Q_3+Q_4+6Q_1^2Q_2$

Table 6.2 – Failure Expressions for parallel systems [11]

Term	2-Path	3-Path	4-Path
Q_1	$(1-\beta)\lambda$	$(1-\beta)\lambda$	$(1-\beta)\lambda$
Q_2	$\beta\lambda$	$0.5\beta(1-\Upsilon)\lambda$	$0.33\beta(1-\Upsilon)\lambda$
Q_3	N/A	$\beta\Upsilon\lambda$	$0.33\beta\Upsilon(1-\delta)\lambda$
Q_4	N/A	N/A	$\beta\Upsilon\delta\lambda$

Table 6.3 – Q-values

For Greek letter values, refer to Table 14.9.

Where a hazard function is available, it can be substituted for λ when analyzing the probability of failure of an asset at a given point in time (e.g. when analyzing power transformer failure risk over time).

7. Risk Quantification – Consequence of Event

This chapter outlines the main categories of consequence associated assets in the event of functional failure. Depending on the asset, some or all of the consequence categories are applicable for asset risk quantification.

7.1. Energy at risk

The key element of asset functional risk is "energy at risk", which is an estimate of the amount of energy that would not be supplied if an asset was out of service, such that the 'system' would not be able to perform its' primary function (the transportation of electricity from one location to another).

This statistic provides an indication of magnitude of loss of load that would arise in the unlikely event of an asset failure.

United Energy estimates energy at risk based on a weighting of the 10th and 50th percentile demand forecasts in alignment with AEMO and the other Victorian Distribution Business. The following risk weightings are used:

Demand forecast	Risk Weighting
10th percentile	30%
50th percentile	70%

Table 7.1 Risk weightings - Energy

7.1.1. Interpreting energy at risk

As noted above, "energy at risk" is an estimate of the amount of energy that would not be supplied if one asset (e.g. a transformer or sub-transmission line) was out of service during the critical loading period(s).

For example, the capability of a zone substation with one transformer out of service is referred to as its "N minus 1" rating. The capability of the station with all transformers in service is referred to as its "N" rating. The relationship between the N and N-1 ratings of a station and the energy at risk is depicted in Figure 7.1 below.

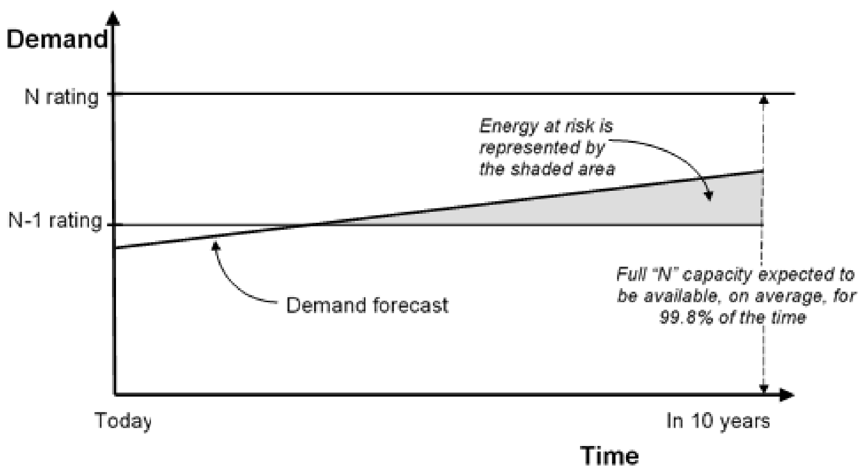

Figure 7.1 Relationship between N, N-1 rating and energy at risk

Note that:

- under normal operating conditions, there will typically be more than adequate zone substation capacity to supply all demand; and
- the risk of prolonged outages of a zone substation transformer leading to load interruption is typically very low.

The capability of a sub-transmission line network with one line out of service is referred to as the (N-1) condition for that sub-transmission network.

- under normal operating conditions, there will typically be more than adequate line capacity to supply all demand; and
- the risk of prolonged outages of a sub-transmission line leading to load interruption is typically very low and is dependent upon the length of line exposed and the environment in which the line operates.

7.1.2. Value of customer reliability (VCR)

In order to determine the economically optimal level and configuration of distribution capacity (and hence the supply reliability that will be delivered to customers), it is necessary to place a value on supply reliability from the customer's perspective.

Estimating the marginal value to customers of reliability is inherently difficult, and ultimately requires the application of some judgement. Nonetheless, there is information available (principally, surveys designed to estimate the costs faced by consumers as a result of electricity supply interruptions) that provides a guide as to the likely value.

United Energy relies upon surveys undertaken by the Australian Energy Market Operator (**AEMO**) to establish the Value of Customer Reliability (**VCR**). AEMO published the following Victorian VCR values in its final report dated 28 November 2014 which have been escalated using the ratio of March 2014 to March 2019 CPI figures as per the AEMO Application Guide to the following amounts:

Sector	VCR for 2019 ($/kWh)
Residential	$26.80
Commercial	$48.41
Agricultural	$51.60
Industrial	$47.70
UE Average	$42.76

Table 7.2 Values of customer reliability

These values are multiplied by the relative weighting of each sector at the zone substation or for the sub-transmission line, and a composite single value of customer reliability is estimated.

This should be used to calculate the economic benefit of undertaking an augmentation, and where the net present value of the benefits outweighs the costs, and is superior to other options, United Energy is likely to proceed with the works.

For the latest VCR please see the Network Planning team.

7.1.3. Value of expected energy at risk

The financial value of expected energy at risk is calculated by multiplying the "energy at risk", the "value of customer reliability", and the "plant unavailability".

7.1.4. Zone Substation Failures

For zone substation plant failures, the energy at risk is calculated based on the projected load profile, assessed hourly, for a calendar year, compared against the available capacity in the event of asset failures. The load use of load transfers should also be assessed which has the impact of lowering the load on the effected zone substation in the event of an outage. From the load profile, calculate;

- The total MWh in the year where the residual load profile exceeds the station's capacity in the event of a plant failure;
- The total MWh in the year where the residual load profile exceeds the station's capacity in the event of two plant failures (two and three transformer stations only);
- The total MWh in the year where the residual load profile exceeds the station's capacity in the event of three plant failures (three transformer stations only);

7.1.5. Distribution Network Feeder Failures

The following utilization ratios should be used to determine average energy levels for distribution feeders in the case where a detailed analysis is not practical. The ratios are based on observed average figures for United Energy feeders. Specific feeder data may be available for more detailed use.

Ratio	Average Utilisation
Peak Demand / Feeder Capacity	50%
Average Demand / Peak Demand	50%
Average Demand / Feeder Capacity	25%

Table 7.3 Average utilization factors

Example: A 22kV Zone Substation feeder has a rating of 300A. In the event of a fault, the feeder loses supply for 30 minutes. The average utilization of the feeder is 25% at a power factor of 0.98; it is assumed that during the time of the fault, a total of (1.73 × 22kV × 75A × 0.98 × 0.5) = 1399kWh. With a VCR of $40/kWh, the value of energy lost during the outage is just under $60,000.

Example: A proposal to install a distribution ACR on a feeder is to be evaluated. With an annual fault rate of 1 per annum, the annual outage cost is $60,000. Installation of an ACR to sectionalize the feeder into two sections will notionally halve the VCR risk to $30,000 per annum – an annual benefit of $30,000. The cost to implement the proposal should include life cycle costs of the asset – installation, maintenance and future unplanned failure.

7.2. Safety Consequence

7.2.1. Likelihood of Consequence

The likelihood of consequence of safety-related incidents is extremely low on the UE network.

In the absence of relevant safety consequence figures for United Energy, figures from Ofgem shall be used unless a specific asset circumstance gives rise to the justification of a different figure.

For a listing of safety consequence parameters, refer to Table 14.1.

7.2.2. Cost of Consequence

For the valuation of safety consequences, refer to Table 14.2.

7.3. Bushfire Consequence

For quantification of bushfire consequences, outputs from the Tolhurst Bushfire Model are used. This is only used on a case-by-case basis for assets that are part of the High Bushfire-risk area. Refer to Table 14.2.

7.4. Environmental Consequence

Environmental-related consequence figures to be advised after review of changes to the Environmental Protection Act.

7.5. Failure / Replacement Costs

In the event of an asset failure, there is associated repair and/or replacement costs to reinstate the system function (Capex/Opex).

Where required, repair and/or replacement costs should be based on historic data or reasonable estimates. Where multiple probabilities of consequence exist for a single probability of failure, a weighted average failure repair cost may be acceptable to use.

8. Distribution Assets: Life Cycle Costing

UE's Asset management Policy includes an objective to manage assets to the least whole of life cycle cost. Depending on how the asset is managed in terms of policy, different levels of Capex, Opex and risk are achieved. This chapter outlines a framework for how this should be assessed for low-value, high-volume assets, where the analysis of individual assets is not practical; instead, groups of assets are assessed using aggregate asset data relating to procurement, operating costs, and risk.

The method of assessing the asset life cycle cost (and the derivation for the annual asset cost for a fleet of assets) has been developed in accordance with the general principles of IEC 61703 and AS IEC 60300.3.3.

Input data into the life cycle cost assessment should be derived from historical data where possible, and are supported by engineering judgement to approximate the quantification of the cost-risk-performance balance. It is recognised that there can be significant year-on-year variation in asset performance based on external factors that are too complex to model: relevant average figures should be used.

Care should be taken to use asset data that is relevant only for the time period for where a particular life cycle management option has been implemented.

The analysis is a living assessment, and is not 'final'; as this method is applied across asset classes, it is expected that the relationships between failure rates, tasks, and maintenance expenditure is further refined, and will be fed back into the analysis of other asset life cycle plans. As asset data is collected and refined, the analysis for each asset should be updated.

It should be noted that asset failure data is not necessarily collated to the granularity or categorisation required to perform the analysis in this chapter. If data is not available, engineering judgement should be used.

For the purposes of this analysis, the life cycle phases that shall be considered are Installation, Operation and Maintenance, and Disposal.

8.1. Abbreviations

For the purposes of this chapter, the following abbreviations are used, based on terms used in AS IEC 60300.3.3.

Abb.	Description
LCC	Total Life cycle cost of an asset
LCC_t	The life cycle cost in year t
L	The typical useful life of an asset
LCCA	Acquisition Cost
LCCO	Operating Cost over its total life
LCCD	Disposal Cost

Table 8.1 – LCC Abbreviations

Unless otherwise specified, asset disposal costs are not costed as the acquisition cost typically includes removal of the old asset.

8.2. Life Cycle Costing - Overview

Thorough assessment of the asset life cycle cost is essential for determination of efficient purchase and maintenance determination practices.

The following is from IEC 60300-3-11:

LCC = Cost acquisition + Cost ownership + Cost disposal

Note that the cost of asset replacement is not included in the Figure above. The cost of an asset replacement is split into two components; cost of disposal of the old asset, and cost of acquisition of the new asset.

For an electricity network asset, the following costs shall be considered:

LCC = Cost acquisition + (t * (Cost planned, annual + Cost unplanned, annual)) + Cost disposal

For an expected normal operating time of t years. The period t shall only consider the normal operating time where the expected failure rate is relatively constant; for assets at the end of their life with an increasing failure rate, a separate analysis is recommended.

All analysis shall be conducted on a per-asset basis. Where the analysis requires comparison of different asset lives, then the annual life cycle cost per asset shall be determined by LCC / t.

8.3. Acquisition (LCCA)

Acquisition costs are split into two key components: direct costs, and indirect costs.

Direct costs shall include the total settled cost of the asset.

8.3.1. Distribution assets

The majority of distribution assets are high volume, low value assets. These are acquired by United Energy through a 'unitised' rate system of repeatable work.

LCCA = Unitised Rate + Costs Investment, Maintenance

= Rate + CS + CT

The following investment and maintenance costs shall be considered where applicable:

Cost Element	Abb.	Description
Spares	CS	Cost of spares. Note where spares are applicable (e.g. FIM).
Training	CT	Cost of additional training. This should only be included where specialist training is required. Care should be taken not to double-count training costs, where training is also included in the asset purchase cost.

Table 8.2 – Investment and Maintenance Cost Elements

If additional costs are required for a particular reason in addition to the Unit rate, these costs should be added and noted separately.

8.3.2. Zone Substation Assets

The majority of zone substation assets are high cost, low volume assets. The acquisition cost is similar, however instead of a 'Unitised' rate, the actual asset cost should be used.

This should not be the 'project' cost to install the asset, but instead the average settled asset value, as a project may involve the installation of multiple assets.

LCCA = Average Asset settled value + Costs Investment, Maintenance

= Cost + CS + CT

8.4. Operating and Maintaining (LCCO)

The operating part of the asset life cycle is the total annual cost of operating and maintaining the asset, multiplied by the number of years the asset will remain useful in a normal operating state.

8.4.1. Maintenance (CY)

This Cost element captures asset costs associated with operating the asset.

Cost Element	Abb.	Description
Preventative	CYP	Cost of routine planned maintenance (i.e. inspections, scheduled maintenance, overhauls, etc.)
Corrective	CYC	Cost of unplanned rectification activities. Note that these costs relate to the repair or restoration of the asset itself, not the consequence cost of the unplanned event. For example, if a circuit breaker fails to trip, the cost of the defect repair would be captured under cost element CYC. The operating consequence cost (i.e. outage costs) would be captured under CO.

Table 8.3 – Maintenance Cost Elements

8.4.2. Operation (CO)

Operation costs include any other operating costs, and losses from unavailability. Typically, an unplanned event has a material and labour cost to rectify, and may or may not have a cost associated with the unavailability. This can include

- Standby losses
- Energy supply risk associated with unavailability (VCR)
- Safety and environmental-related costs
- Other risk costs e.g. fire start costs

These costs typically relate to the failure consequence of operating an asset. This area is comprehensively discussed in Section 5.

8.5. Disposal (LCCD)

Cost to dispose of or recycle the asset.

This cost is generally included in the acquisition cost for UE assets, and is typically set as zero.

8.6. Worked Example: LV Overhead Services

For this worked example, the current cost of LV overhead services is assessed. The following data is used in the analysis:

- Acquisition cost of $650
- Average replacement rate of 7000 services / year
- Failure rates as follows: 0.046 (3rd party), 1.249 (vegetation), 0.353 (electrical/mechanical) failures / 1000 services / year
- No directly attributed asset inspection program
- Consequence: 20% probability of an outage (all failure types), 18% probability of an electric shock (electrical/mechanical failures only)
- Consequence costs: ; $31.50 for an outage; $381,000 for an injury/electrical shock

The average life of services can be estimated as:

$$Average\ life = \frac{365{,}000}{7000} = 52.1\ years$$

Note: this approach assumes an evenly-distributed age profile. For greater accuracy, it is recommended that asset groups are broken into sub-groups with different risk profiles. This is only possible if failure and replacement data is captured by sub-group.

The annual failure cost per service is assessed to be:

CYC = (0.046 + 1.249 + 0.353) / 1000 x 20% x $31.50 + 0.353 / 1000 x 13% x $381,000

= $0.01 + $17.48 = $17.49 / year

The predominant failure risk cost is safety-related.

The total life cycle cost for an overhead service is:

LCC = $650 + (52.1 * $17.49) + $0 = $1561.23 or $29.97 / year

9. Option Analysis

Where a risk is identified, a number of means may be practically available to reduce the risk to acceptable levels (or if possible, eliminate the risk); each possibility is known as an ‘Option’.

The risk(s) identified may focus on;

- An individual element of the system – an ‘asset’ risk;
- The system as a whole e.g. zone substation energy at risk.

The whole of life cost for an option to manage an asset comprises three elements:

- Capital Expenditure (Capex)
- Operating and Maintenance Expenditure (Opex)
- Risk (refer Chapter 5).

The three elements are linked; an understanding of the relationship between them is essential to quantifying the outcomes of possible options, and the tradeoffs that are expected when increasing or decreasing one or more of the three elements.

Example: For a fleet of 100 switches, the failure rate is a function of the level of routine maintenance, and number of proactive replacements implemented each year. If the routine maintenance is decreased, it can be expected that the number of failures will increase; conversely, if the number of failures is required to be reduced, then the amount of capital and/or operational expenditure will need to increase.

Examples of typical options are included below.

9.1. Typical Standalone Asset Options

9.1.1. Status Quo

This option refers to the existing operational case; continuing to operate the asset according to current policies.

Sometimes, this is referred to as the ‘do nothing’ option; this can be interpreted as literally ‘do nothing’. However, for many assets, some activities are performed to manage the risk. This should be interpreted as ‘do nothing different’.

Example: A ZSS transformer may have routine oil testing and OLTC and Bushing tests. In evaluating the economic case for asset replacement, the ‘Do nothing’ option does not indicate ‘do nothing to maintain the asset, therefore the OLTC or bushings are likely to fail; rather, continue to perform routine maintenance as per current business policies’.

9.1.2. Changing the existing Assets

This involves performing work that replaces or modifies the asset (or operation of) in some way. Some examples include;

- Replacing an asset with a modern equivalent
- Replacing a component of an asset
- Modifying the operation of the asset in some way (e.g. protection setting change or operational restriction)

9.1.3. System-related Options

These are explored in more detail in Section X below.

9.1.4. Non-network Options

This relates to other parties providing non network options to provide a solution to solve or defer the need for investment on the network. For example, paying a customer to reduce demand on the system to reduce the level of risk to an acceptable level rather than replacing an asset does not require any work on a UE asset or a system, however the risk is managed.

9.2. System - related Options

The following options are available to modify the behavior of the overall system;

- Augmentation – for example additional parallel paths may be created, generally adding supply capacity to the distribution system.
- Performance – where the behaviour of a system generally comprised of series components is modified by changing the characteristic of a component, or inserting a new component in series. Note that this may also apply to Asset-related options e.g. fitment of possum-proofing to a substation.

When assessing option analysis, consideration should be given to understanding and quantifying the outcomes of modifying system by changing or adding assets. Where systems are modified in some way, there are typically positive and negative effects associated with all system changes; these should be understood and quantified so that assessing the option includes the upsides and downsides of system changes.

Note: for simplicity, these examples assume a constant failure rate.

Example: an additional ZSS transformer is proposed to be installed within a substation, in parallel with two existing transformers. Whilst the additional item improves the overall electricity reliability of the substation through the addition of a redundant path, the additional item will have increased operating costs by 50%, as well as the failure rate of the substation (as there are now three items that have to be maintained, and may fail, instead of two).

Example: in order to reduce the effective span length of a bay of 22kV conductor, a HV spreader (comprising 2 insulators) is installed mid-span to reduce the likelihood of conductor clashing whilst energized. However, from a item perspective, an additional 2 insulators has increased the number of insulators from 6 to 8 (assuming 3 insulators at the pole at each end of the span), as well as increasing the number of work points on conductors from 6 to 9. These actions will increase the number of insulator or conductor failures.

9.3. Risk Reduction

It is rare that risk can be practically eliminated; for Option analysis, different options may reduce the level of risk by differing amounts. The risk analysis outlined in Section 5 primarily discusses quantification of risk; the risk analysis should be repeated, as different options may address some, but not all failure modes.

9.4. Worked Example: LV Services

The analysis in Section 8.6 is not inherently useful by itself, but is when a number of different management approaches are considered, so that the least-cost option (or option with a desired outcome) can be implemented.

A proposal to implement a 2-yearly standalone inspection program for all LV services is considered: this is expected to increase the annual number of replacements to 10,000, and estimated to decrease the number of failures by 25%. The cost per inspection is $20 ($10/service/year).

The new average life of services can be estimated as:

$$Average\ life = \frac{365{,}000}{10{,}000} = 36.5\ years$$

The annual operating costs per service are assessed to be:

CYC = (0.046 + 1.249 + 0.353) / 1000 x 20% x $31.50 + 0.353 / 1000 x 13% x $381,000

= ($0.01 + $17.48) x 75% = $13.11 / year

CYP = $10.

The total life cycle cost for an overhead service is:

LCC = $650 + (36.5 x ($13.11 + $10) + $0 = $1493.63 or $40.92 / year

The proposed program does not result in a lower overall cost when compared with the current approach. However, the analysis may change when assessing a sub-group of assets. In order to do this, failure and replacement data will need to be available for each sub-group; if it is not, then engineering judgement will need to be used to apportion failure data to different sub-groups.

9.5. Worked Example: ZSS Transformer Replacement

A zone substation with a pair of 50-year old transformers in 2018 is considered. The failure rate for the transformers is assessed to be 1% at 50 years of age and rising. The substation is loaded below 'N-1' levels, and has been configured to receive the relocatable transformer in the event of a failure in 30 days. The substation transformers are identically constructed and operated; for this asset class, common-cause failures have been observed. Safety risk figures from Table 14.1 and Table 14.2 are used.

(The analysis assumes that the asset is operating beyond its useful life).

Using the methods outlined in Sections 6.5 and 7.1 , the annual energy at risk at the substation is assessed to be 1900 kWh. The failure risk cost and minor risk cost for both transformers is 2%.

The total cost today for the transformers at the substation is assessed to be:

Cost = 1900 x $42.20 + (2% x $28,058) + (2% x 77% x $2M + 2% x 23% x $200k)

= $112,461 in 2018

The option to replace a transformer is considered, with a replacement cost of $2M and WACC of 5%. Repeating the analysis reduces the energy at risk at the station to 300 kWh

Cost (station risk) = 300 x $42.20 = $12,660/yr

Risk Cost (old transformer) = (1% x $28,058) + (1% x 77% x $2M + 1% x 23% x $200k) = $16,141/yr

Risk Cost (new transformer) = (0.01% x $28,058) + (0.01% x 77% x $2M + 0.01% x 23% x $200k) = $161.41/yr

New Asset Cost = $100,000/yr

Total annual option cost = $100,000 + $12,660 + $16,141 + $161.41 = $128,962

Even though the risk is halved with this option, when the cost of the new asset is considered, it is not the least-cost option today. The risk should be re-evaluated each year with an increased failure probability and load forecast until the total risk exceeds $129,000 in a given year.

An alternative non-replacement option is also considered: by fitting a set of online monitors, the probability of failure can be reduced. It is assumed that the installed cost is $500k, which reduces the probability of unplanned failure by half. By doing this, the station energy at risk is reduced to 700 kWh in 2018.

Cost (station risk) = 700 x $42.20 = $29,540

Risk Cost (transformers) = (1% x $28,058) + (1% x 77% x $2M + 1% x 23% x $200k) = $16,141/yr

New Asset Cost = $25,000yr

Total annual option cost = $25,000 + $16,141 + $29,540 = $70,681

Thus, the online monitoring system proves to be a lower-cost option today. However, continuing to operate older assets will result in an increase in risk over time. If the annual risk is assumed to increase by $10,000 per annum, the risk over time can be assed. This is demonstrated below in Table 9.1 .

	2018	2019	2020	2021	2022	2023	2024	2025
Status Quo	$112.5k	$122.5k	$132.5k	$142.5k	$152.5k	$152.5k	$152.5k	$152.5k
Replace 1 transformer	$129k	$129k	$129k	$129k	$129k	$129k	$129k	$129k
Online Monitor	$70.7k	$80.7k	$90.7k	$100.7k	$110.7k	$120.7k	$130.7k	$140.7k

Table 9.1 – ZSS Transformer Option comparison total cost

When comparing all option costs, it is clear that:

- The replacement of one of the aged transformers is economic in 2020;
- A significant risk reduction can be achieved by installing an on-line monitoring system immediately to these transformers. When comparing this option to the replacement option, the optimal timing becomes 2024.

Hence, the installation of an online-monitoring system allows for the deferral of asset replacement at the zone substation by 4 years.

10. Sensitivity Analysis

Asset-related data is not always available; in some cases it is estimated, or can vary year-on-year. When performing analysis, sensitivity to input parameters should be considered to see if a different option may prove to be better for different scenarios. This serves as an ancillary input into the decision-making process.

The following table is a list of suggested variances for key parameters, based on assessed confidence limits, industry data, or engineering judgement based on the amount of failure data.

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Parameter	Sensitivity	Comment
VCR	No change	
WACC	± 10%	
Safety	No change	
Load forecast	± 4%	
Capex / Opex	± 10%	
Probability of Failure	± 20%	

Table 10.1 –Asset Sensitivity parameters

When conducting sensitivity analysis, the list of parameters that alter the outcome can be quite large; it is recommended that a preliminary assessment is conducted to determine which parameters have the greatest effect of the recommended output option, and perform analysis on these.

For zone substation asset replacement projects, it is recommended that the following additional scenarios are modelled for consideration;

- WACC, Capex/Opex up and Load growth down
- WACC, Capex/Opex down and Load growth up
- Probability of Failure up
- Probability of Failure down

11. Asset Performance

Asset performance metrics are a wide area, and should be set in each asset Life Cycle strategy when considering the defined functions for the asset in question. Examples include:

- Number of asset failures
- Expected annual maintenance cost
- Expected number of customer outage minutes (SAIDI) attributed to the asset failures

Where multiple options are assessed (for example, considering time-based maintenance versus pro-active replacement), the expected asset performance metrics for each option should be considered and documented for use in decision making within the wider business. Such options may not be limited to the replacement and maintenance of assets; options can include system design changes that alter functional behaviour. For example, the addition of a ZSS transformer to a zone substation will increase the redundancy and hence improve the reliability of the site.

It is practically impossible to statistically prove the change in performance for a change in option analysis in a number of cases; in such cases, the quantification is likely to be subjective, based on the expert judgement of the asset engineer, compiled from experience from other businesses, knowledge of the asset and deterioration rates for varying failure modes.

Example: for an asset that has been maintained at time interval X for a number of years resulting in a failure rate of I assets per annum, there may be no data available to demonstrate the expected increase in failure rate if the maintenance time interval is increased to Y. In such a case, the engineer’s judgement is the only tool available.

12. References

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13. Appendix A – Asset Function Definitions

Table 13.1 – Asset Function Definitions

Item	Asset LCS	Intended Functions	Functional Failure Example	Comments
UE Network	UE PL 2000	Enable the transfer of electrical energy from supply sources to loads.	Supply outage to a customer	UE Network
Poles	UE PL 2005 - Poles	Provide mechanical support for conductors and other pole mounted assets Provide clearance (e.g. phase to ground)	Pole fell to ground Pole snapped Zero resistance to bending moment	Poles
Crossarms	UE PL 2006 – Pole Top Structures	Provide mechanical support for conductors Provide clearance (e.g. phase to phase and phase to ground)	Crossarm snapped	Crossarms
Insulators	UE PL 2006 – Pole Top Structures	Provide phase-ground insulation for conductors	Insulator broken or deteriorated and failed to provide adequate insulation e.g. tracking	Insulators
Connectors	UE PL 2007 – Connectors and Conductors	Provide connection between conductors	Connector burned out	Connectors
Conductors	UE PL 2007 – Connectors and Conductors	Provide electrical circuit from the source to load.	Broken and fell on to the ground Tree or animal contact with conductor	Conductors
Disconnectors	UE PL 2008 – Overhead Line Switchgear UE PL 2026 – ZSS Disconnectors and Buses	Disconnect and connect electrical circuit (unloaded current) Provide sufficient insulation strength (e.g. phase to phase and phase to ground) Provide a point of isolation	Failed to operate Flashover (e.g. phase to phase or phase to earth)	Disconnectors
HV Air Break Switches (ABS)	UE PL 2008 – Overhead Line Switchgear	Disconnect and connect electrical circuit (load current) Provide sufficient insulation strength (e.g. phase to phase and phase to ground) Provide a point of isolation	Failed to operate Failed to interrupt load current Flashover phase to phase / phase to earth	HV Air Break Switches (ABS)

Item	Asset LCS	Intended Functions	Functional Failure Example	Comments
HV Manual Gas Switches (MGS)	UE PL 2008 – Overhead Line Switchgear	Disconnect and connect electrical circuit (load current) Provide sufficient insulation strength (e.g. phase to phase and phase to ground) Provide a point of isolation	Failed to operate Failed to interrupt load current Flashover phase to phase / phase to earth Failed to provide correct status indication	HV Manual Gas Switches (MGS)
HV Remote Controlled Gas Switches (RCGS)	UE PL 2008 – Overhead Line Switchgear	Disconnect and connect electrical circuit (load current) Provide sufficient insulation strength (e.g. phase to phase and phase to ground) Provide a point of isolation	Failed to operate Failed to interrupt load current Flashover phase to phase / phase to earth Failed to provide correct status indication	HV Remote Controlled Gas Switches (RCGS)
LV Switches	UE PL 2008 – Overhead Line Switchgear	Disconnect and connect electrical circuit (load current) Provide sufficient insulation strength (e.g. phase to phase and phase to ground) Provide a point of isolation	Failed to operate Failed to interrupt load current Flashover phase to phase / phase to earth Failed to provide correct status indication	LV Switches
Capacitor Cans	UE PL 2009 – Overhead Line Capacitors UE PL 2022 – ZSS Capacitors	Provide VAR and voltage support	Bulged capacitor can Unacceptable capacitance reading	Capacitor Cans
Capacitor Vacuum Switches	UE PL 2009 – Overhead Line Capacitors	Disconnect and connect capacitor banks Provide sufficient insulation strength (e.g. phase to phase and phase to ground)	Failed to open / close Flashover (e.g. phase to earth)	Capacitor Vacuum Switches
Control boxes	UE PL 2009 – Overhead Line Capacitors	Monitor and control the capacitor bank units	Failed to control Failed to provide status	Control boxes
Automatic Circuit	UE PL 2010 – Automatic Circuit Recloser	Disconnect and connect electrical circuit (fault current)	Failed to operate Failed to interrupt fault current	Automatic Circuit Reclosers (ACR)s

Item	Asset LCS	Intended Functions	Functional Failure Example	Comments
Reclosers (ACR)s		Provide sufficient insulation strength (e.g. phase to phase and phase to ground)	Internal/external flashovers	
ACR and RCGS Controllers	UE PL 2010 – Automatic Circuit Recloser	Monitor and control the ACR units	Failed to control the ACR Failed to indicate correct status	ACR Controllers
Voltage Transformers (VTs)	UE PL 2010 – Automatic Circuit Recloser UE PL 2008 – Overhead Line Switchgear	Provide power to the control box Provide sufficient insulation strength (e.g. phase to phase and phase to ground)	Flashover Failed to power to the control box	Voltage Transformers (VTs)
Public lights	UE PL 2011 – Public Lighting	Provide sufficient light / illumination on the ground	Lights not working or providing insufficient insulation	Public lights
HV Fuses	UE PL 2012 – HV Outdoor Fuses	Interrupt fault current	Fuse candling	HV Fuses
HV Surge Arresters	UE PL 2013 – HV Surge Arresters	Limit the overvoltage levels to LIWL of the equipment associated Provide sufficient insulation strength (e.g. phase to phase and phase to ground)	Internal flashover Failed to protect plants under overvoltage conditions	HV Surge Arresters
Transformers	UE PL 2014 – Pole Type Transformers UE PL 2015 – Non Pole Substations	Transform voltage from HV to LV Provide sufficient insulation strength (e.g. phase to phase and phase to ground)	Transformer internal flashover	Transformers
Transformers	UE PL 2028 – ZSS Transformers	Transform voltage from HV to LV Provide sufficient insulation strength (e.g. phase to phase and phase to ground)	System includes sub-components such as bushings and OLTCs	Transformers
Switchgear – Ring Main Unit (RMU)	UE PL 2015 – Non Pole Substations	Disconnect and connect electrical circuit (fault current) Provide sufficient insulation strength (e.g. phase to phase and phase to ground)	Flashover Failed to operate Unable to operate (e.g. due to low gas)	Switchgear – Ring Main Unit (RMU)
Earth	UE PL 2016 – Earth	Provide a safe return path for current	Earthing resistance too high	Earth

Item	Asset LCS	Intended Functions	Functional Failure Example	Comments
Cables	UE PL 2017 – Underground Distribution Systems UE PL 2007 – Connectors and Conductors	Provide electrical circuit from the source to load. Provide sufficient insulation strength (e.g. phase to phase and phase to ground)	Flashover to earth	Cables
Cable joints and terminations	UE PL 2017 – Underground Distribution Systems UE PL 2007 – Connectors and Conductors	Provide connection between conductors Provide sufficient insulation strength (e.g. phase to phase and phase to ground)	Flashover to earth	Cable joints and terminations
LV Pillars and Cabinets	UE PL 2017 – Underground Distribution Systems	Provide electrical circuit from the source to load Provide sufficient insulation strength (e.g. phase to phase and phase to ground) Provide the ability to operate and isolate	Failed to operated Flashover	LV Pillars and Cabinets
Overhead Services	UE PL 2018 – LV Services and Terminations	Provide electrical circuit from the source to load.	Broken and fell on to the ground High resistance neutral	Overhead Services
Underground Services	UE PL 2018 – LV Services and Terminations	Provide electrical circuit from the source to load. Provide sufficient insulation strength (e.g. phase to phase and phase to ground)	Flashover High resistance neutral	Underground Services
Buildings	UE PL 2019 – Buildings and Grounds	Provide protective housing to electrical equipment from the external environment	Building collapsed Roof leaks after heavy rain	Buildings
Fences	UE PL 2019 – Buildings and Grounds	Prevent entry from unauthorized persons	Substation break-in / theft occurs	
Circuit Breakers	UE PL 2023 – ZSS CBs	Open/interrupt and close/reclose on demand Provide insulation between conduction paths and ground	Failed to interrupt fault current Internal flashover due to insufficient dielectric strength	Circuit Breakers
Current Transformers	UE PL 2024 – ZSS Instrument Transformers	Transform current into a measuring levels	Failed to transform current Flashover	Current Transformers

Item	Asset LCS	Intended Functions	Functional Failure Example	Comments
		Provide sufficient insulation strength (e.g. phase to phase and phase to ground)		
Voltage Transformers	UE PL 2024 – ZSS Instrument Transformers	Transform voltage into a measuring levels Provide sufficient insulation strength (e.g. phase to phase and phase to ground)	Failed to transform voltage Flashover	Voltage Transformers
Battery Banks	UE PL 2025 – ZSS DC Systems	Provide DC power to equipment	Failed to supply DC power	Battery Banks
Battery Chargers	UE PL 2025 – ZSS DC Systems	Maintain the battery voltage at the required level	Failed to charge the battery banks	Battery Chargers
Earthing Switches	UE PL 2026 – ZSS Disconnectors and Buses	Provide low resistance path to earth Provide the ability to operate	Failed to operate High resistance	Earthing Switches
Relays	UE PL 2027 – ZSS Protection and Control Relays	Automatically operate protective equipment Sense abnormal operating conditions and trip primary plants	Failed to operate during a fault Inadvertent trip	Relays
Transformer	UE PL 2028 – ZSS Transformers	Step-down the sub-transmission voltage to the required distribution voltage Regulate system voltage as required Provide sufficient insulation strength (e.g. phase to phase and phase to ground) Act as a system source	Flashover Failure to provide required bus voltage Failure to provide expected capacity	Transformer
Neutral Earthing Resistors (NER)	UE PL 2028 – ZSS Transformers	To provide required impedance To provide a path from system neutral to ground	Flashover Failure to provide a connection to ground	Neutral Earthing Resistors (NER)

14. Appendix B – Probability and Consequence Tables

All failure rates defined in this table are reflective of the asset management practices currently employed by United Energy, and contingent upon the operating limits, maintenance practices, condition-monitoring techniques and replacement recommendations specified within the relevant Asset life cycle strategy. If these limits, practices and techniques are not adhered to, the failure rates can be reasonably expected to increase beyond those specified within this table.

14.1. Probability of Consequence – Safety – All Assets

As UE has limited data relating to safety events, the figures that are advised to be used are given in Table 14.1 unless safety incident data (e.g. from ESV reports) is available.

Asset	LTI	Public	Staff
LV Poles	0.000816	0.00003264	0.00001632
11/22kV Poles	0.000272	0.00001088	0.00000544
66kV Poles	0.000272	0.00001088	0.00000544
Conductor (All)	0.000544	0.00002176	0.0001088
Underground Cable >1kV	0.00000075	0.000000075	0.000000075
HV Insulators	0.000544	0.00002176	0.0001088
Distribution Transformer	2.60274E-05	0.00023	0.000196062
ZSS Power Transformer	0.000260274	0.000115	0.001960616
ZSS Circuit Breaker	0.000260274	0.000115	0.001960616
Instrument Transformer	0.000260274	0.000115	0.001960616
Secondary	0.000260274	0.000115	0.001960616

Table 14.1 – Probability of Consequence (Safety) [2]

Safety-related consequence	Value ($2019)	Source
Injury (LTI)	$129k	$116k ($2013), adjusted for inflation Safe Work Australia report ‘The Cost of Work-related Injury and Illness for Australian Employers, Workers and the Community 2012-2013’.
Death (VSL)	$4.56M	$4.2M ($2014), adjusted for inflation Department of Prime Minister and Cabinet, Best Practice Regulation Guidance Note: Value of statistical life, December 2014
Fire	N/A	When evaluating bushfire-risk specific projects, consequence costs can be derived from the Tolhurst Fire model.

Table 14.2 - Safety Consequence Costs

14.2. Distribution Asset Failure Rates

The failure rates below have been calculated from outage data and incident reports 2013-2017. For some assets (e.g. sub-transmission connector failures), data is not available. The list only includes data available at the time of writing, and is not exhaustive.

<table>
<tr><th>Asset</th><th>Failure Mode</th><th>(Faults/1000 assets/ yr or Faults/100 km/yr)</th><th>Comment</th></tr>
<tr><td>Pole (HV/ST)</td><td>All Modes</td><td>$\alpha = 5.9, \beta = 209$</td><td></td></tr>
<tr><td>Pole (LV)</td><td>All Modes</td><td>$\alpha = 5.9, \beta = 201$</td><td></td></tr>
<tr><td>Pole (HV)</td><td>Mechanical</td><td>0.045</td><td rowspan="6">5-year average
Faults / 1000 assets / yr</td></tr>
<tr><td></td><td>Vehicle Impact</td><td>0.686</td></tr>
<tr><td>Pole (LV)</td><td>Mechanical</td><td>0.017</td></tr>
<tr><td></td><td>Vehicle Impact</td><td>1.804</td></tr>
<tr><td>Pole (SubT)</td><td>Mechanical</td><td>0.246</td></tr>
<tr><td></td><td>Vehicle Impact</td><td>0.239</td></tr>
<tr><td>HV Conductor</td><td>Vegetation</td><td>0.228</td><td rowspan="5">5-year average
Faults / 100km / year</td></tr>
<tr><td></td><td>Mechanical</td><td>0.356</td></tr>
<tr><td></td><td>Animal</td><td>0.055</td></tr>
<tr><td></td><td>Lightning</td><td>0.009</td></tr>
<tr><td></td><td>Vehicle</td><td>0.078</td></tr>
</table>

Asset	Failure Mode	(Faults/1000 assets/ yr or Faults/100 km/yr)	Comment
LV Conductor	Vegetation	0.302	5-year average Faults / 100km / year
	Mechanical	0.305	
	Animal	0.000	
	Lightning	0.003	
	Vehicle	0.055	
HV Connector	Vegetation	0.064	5-year average Faults / 100km / year
	Mechanical	0.360	
	Animal	0.073	
	Lightning	0.023	
	Vehicle	0.005	
LV Connector	Vegetation	0.038	5-year average Faults / 100km / year
	Mechanical	0.233	
	Animal	0.000	
	Lightning	0.000	
	Vehicle	0.014	
HV Cross-arm	Mechanical /Animal	1.25	5-year average Faults / 1000 wood assets / yr
LV Cross-arm	Mechanical / Animal	0.34	
Distribution Transformers <=1000kVA	Overall (within Cyclic loading)	0.33	5-year average Faults / 1000 assets / yr
	Overall (above Cyclic loading)	1.12	
Distribution Transformers > 1000kVA	Overall (within Cyclic loading)	1.33	5-year average Faults / 1000 assets / yr
	Overall (above Cyclic loading)	6.35	

Asset	Failure Mode	(Faults/1000 assets/ yr or Faults/100 km/yr)	Comment
Pole Type Transformers	All Modes	TBA	
Kiosk Transformers	All Modes	$\alpha = 5.0$, $\beta = 80$	
Ground/Indoor	All Modes	TBA	

Table 14.3 – Distribution Asset Failure Rates

The failure consequences below have been calculated from outage data and incident reports. For some assets (e.g. sub-transmission connector failures), data is not available. The list only includes data available at the time of writing based on average data for 2013-2017, and is not exhaustive.

Asset	Consequence	Probability of Consequence	Cost of Consequence	Comment
Pole (HV)	Outage	1	$29922	
	Safety	As per Table 14.1	As per Table 14.2	
	Fire Start	0	N/A	Allocated to Cross-arm or conductor
Pole (LV)	Outage	1	$2328	
	Safety	As per Table 14.1	As per Table 14.2	
	Fire Start	0	N/A	Allocated to Cross-arm or conductor
Pole (SubT)	Outage	Nil		
	Safety	As per Table 14.1	As per Table 14.2	
	Fire Start	0	N/A	Allocated to Cross-arm or conductor
HV Conductor	Outage	1	$134,815	5-year average data
	Safety	As per Table 14.1	As per Table 14.2	
	Fire Start	0.2 (Mechanical) 0.25 (Vegetation)	As per Table 14.2	
LV Conductor	Outage	1	$7,779	5-year average data
	Safety	As per Table 14.1	As per Table 14.2	
	Fire Start	0.2 (Mechanical)	As per Table 14.2	5-year average data

Asset	Consequence	Probability of Consequence	Cost of Consequence	Comment
		0.25 (Vegetation)		
HV Connector	Outage	1	$80,527	5-year average data
	Safety	Nil	N/A	
	Fire Start	Nil	N/A	
LV Connector	Outage	1	$5,855	5-year average data
	Safety	Nil	N/A	
	Fire Start	Nil	N/A	
HV Crossarm	Outage	1	$81,419	5-year average data
	Safety	As per Table 14.1	As per Table 14.2	Refer 'HV Insulator'
	Fire Start	53%	As per Table 14.2	5-year average data
LV Crossarm	Outage	1	$5707	5-year average data
	Fire Start	1%	As per Table 14.2	5-year average data

Table 14.4 – Distribution Asset Consequences

The following failure rates should be used for LV service analysis.

Asset	Failure Mode	Faults/1000 assets/ yr	Comment
LV Overhead Service (All types)	3rd Party	0.046	5-year average Faults / 1000 assets / yr
	Vegetation	1.249	
	Mechanical / Fatigue / Electrical	0.353	

Table 14.5 – LV Service Failure Rates

Asset	Consequence	Probability of Consequence	Cost of Consequence	Comment
LV Overhead Service (All types)	Outage	20%	$31.50	Based on UE data
	Fire	0.4%		
LV Overhead Service (Neutral Screen)	Safety	10%	As per Table 14.2	Based on UE data
LV Overhead Service (PVC Twisted)	Safety	20%	As per Table 14.2	Based on UE data

Table 14.6 – LV Service Consequences

14.3. Zone Substation and Sub-Transmission Asset Failure Rates

The failure rates quoted below are relatively low, and generally lower than published studies of failure rates. This is a reflection of UE's current asset management practices for ZSS assets, which involve proactive condition assessment, condition and time-based maintenance, and replacement of deteriorated components upon identification to minimise the in-service failure rate.

The limited data available does mean that there is low confidence in the data; however, figures are only included where the calculated failure rate correlates with UE's historic experience.

The list only includes data available at the time of writing, and is not exhaustive.

Asset	Failure Mode	Failure Rate / Hazard Function	Comment
ZSS Transformer	Winding Failure	α =3.6, β = 105	Based on UE failure data
	Bushing Failure	Refer UE PL 2028	Proportionally derived from Winding failure data and Australian utility transformer survey failure rates
	OLTC Failure		
	Other Failures		
Indoor Switchgear Panel	Failure requiring repair or replacement	α =9.8, β = 80	Based on UE failure data
Outdoor Circuit Breaker	Failure requiring repair or replacement	α =9.8, β = 80	Indoor panel rate used
Sub-Transmission Line	All	4.8 Faults / 100km / year	

Table 14.7 – Zone Substation Asset Failure Rates

The failure consequences below have been calculated from incident reports, failure history and relevant literature. The list only includes data available at the time of writing, and is not exhaustive.

Asset	Consequence	Probability of Consequence	Cost of Consequence	Comment
ZSS Transformer - Winding	Repair Costs	100% non-repairable		
	Outage	100% 6 month outage	To be individually assessed	Calculated from Station load profile model
	Fire Start	0%		
ZSS Transformer - Bushing	Repair Costs	80% - repairable 20% - non-repairable	$200k - repairable	Based on UE failure data and experience
	Outage	80% - 24 day outage 20% - 6 month outage	To be individually assessed	Calculated from Station load profile model

Asset	Consequence	Probability of Consequence	Cost of Consequence	Comment
	Fire Start	100%	As per Table 14.2	Based on historic failures
	Safety	As per Table 14.1	As per Table 14.2	Porcelain Bushings only. Polymer bushings – N/A
ZSS Transformer - OLTC	Repair Costs	50% - repairable 50% - non-repairable	$200k - repairable	
	Outage	50% - 24 day outage 50% - 6 month outage	To be individually assessed	Calculated from Station load profile model
	Fire Start	50%		
	Safety	As per Table 14.1	As per Table 14.2	
ZSS Transformer - Other	Repair Costs	50% - repairable 50% - non-repairable	$200k - repairable	E.g. Cable box
	Outage	50% - 24 day outage 50% - 6 month outage	To be individually assessed	Calculated from Station load profile model
	Fire Start	50%	As per Table 14.2	
	Safety	As per Table 14.1	As per Table 14.2	
Indoor Switchgear Panel (Feeder) Mechanism Failure	Outage	1 hour outage	To be individually assessed	No other consequence
Indoor Switchgear Panel (Feeder) Insulation Failure	Outage	2 hour outage	To be individually assessed	
	Repair / replacement Costs	80% panel repair 15% - bus damage 5% - fault affects entire switchboard	80% - $200k 15% - $1M 5% - $3M	
	Safety	As per Table 14.1	As per Table 14.2	
Common-cause event	Overlap Outage duration	Originating event duration *minus* median time to subsequent event	As per originating event	Other consequences as per originating event

Table 14.8 – Zone Substation Asset Failure Consequences

The following values of β shall be used for conditional probability analysis of substation plant. These figures have been derived from UE substation failure data. The figures take into account the detection capability of a common cause failure before the failure occurs in all paths by classifying failures where a second common-cause failure has been prevented as a non-common failure [3].

In the event of a scenario not prescribed below, a different β should be determined based on knowledge about the similarities and differences of the plant being assessed.

Condition	β
Two identical assets operating in parallel; spare not available – 6 month procurement time (e.g. ZSS Transformer)	0.24
Two identical assets operating in parallel; spare not available – 4 month procurement time (e.g. ZSS Switchboard repair)	0.22
Two identical assets operating in parallel; spare readily available, 1 month turnaround time	0.15
Two identical assets operating in parallel; spare readily available, 1 week turnaround time	0.08
Two different assets operating in parallel in the same geographical location	0.05
Two different assets operating in parallel in the same geographical location with additional specific controls to reduce CCF	<0.05
Three assets operating in parallel; two are identical (β), the third is different	β = as per above ϒ = 0.05
Four assets operating in parallel; two are identical, assets three and four are different to the two identical units and each other	β= as per above ϒ = δ = 0.05

Table 14.9 – Standard β-values (MGL)

14.4. Zone Substation Secondary Asset Failures

The failure rates quoted below are calculated from UE failure and replacement rates, and are a reflection of UE's current asset management practices which include proactive condition assessment, condition and time-based maintenance, and replacement of deteriorated components upon identification to minimise the in-service failure rate.

Asset	Failure Mode	Failure Rate / Hazard Function	Comment
Electromechanical Relay	Failure to Operate	α =6.0, β = 75	Based on UE failure data
Analogue Relay	Failure to Operate	α =4.0, β = 56	Based on UE failure data
Digital/Numerical Relay	Failure to Operate	α =3.0, β = 36	Based on UE failure data

Table 14.10 –Secondary Asset Failure Rates

Asset	Consequence	Probability of Consequence	Cost of Consequence	Comment
Protection Relay – Electromechanical	Outage	37% - bus outage 16% - feeder	To be individually assessed	Based on UE failure data
Protection Relay – Analogue	Outage	32% - bus outage 16% - feeder	To be individually assessed	Limited Data – based on Electromechanical data
Protection Relay – Digital/Numerical	Outage	21% - bus outage 9% - feeder	To be individually assessed	Based on UE failure data
Protection Relay – all types	Repair/ Replacement Costs	100%	140k$ - Legacy relay and scheme replacement 20k$ - Relay replacement with identical spare	Other factors (e.g. space restrictions, scheme integrity etc. can affect replacement costs)
Protection Relay – all types	Safety	As per Table 14.1	As per Table 14.2	

Table 14.11 –Secondary Asset Consequences

14.5. ZSS Building and Grounds Failures

The following table gives the functional failure rates for zone substation buildings and grounds, derived from 2013-17 event data.

Asset	Failure Mode	Failure Rate / Hazard Function	Comment
Weatherboard / AC clad building	Failure to protect plant from elements	α =6.8, β = 69	Derived from UE failure data (ceiling collapse / damaged plant.
All buildings	Injury from lead paint exposure	10% if frequently trafficked, (stores/site works) or in mess rooms 2% if not trafficked frequently	Only if present
Fence	Failure to prevent entry	4.7%	Derived from UE failure data

Table 14.12 – Building and Grounds Asset Failure Rates

Asset	Consequence	Probability of Consequence	Cost of Consequence	Comment
Weatherboard / AC clad building	Repair Costs	100%	$200k	PoC is dependent on failure rate calibration
Lead paint injury	Safety	Per Table 14.12	Per Table 14.2	
Fence	Repair Costs	100%	$20k	Lock repair and loss of materials (copper earths)

Table 14.13 – Building and Grounds Consequences