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NARM Methodology

SPT / SSENT Network Asset Risk Annex (NARA)

ISSUE 1
REVISION 1

Revision Record

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Version 18	Initial submission to Ofgem	SHE Transmission	July 2018
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NARM Methodology SPT-SSENT NARA Issue 1	Introduce the calculation methodology for Long-term risk benefit in section 9 in substitution of Risk Trading Model Update section 10 with the title Asset Interventions instead of Network Output Measures and updates in the intervention definitions to be aligned with latest RIGs. Housekeeping modifications and other minor or not significant changes throughout the document in order to correct errors, references or clarify some content.	SP Transmission/SSENT	December 2021
NARM Methodology SPT-SSENT NARA Issue 1	Update section 2 with title, EOL modifier (including forecast of the EOL content now in section 7)	SP Transmission/SSENT	November 2022
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NARM Methodology SPT-SSENT NARA Issue 1	Add section 12- Condition Assessment Methodologies	SP Transmission/SSENT	November 2022

| NARM Methodology SPT-SSENT NARA Issue 1 | Add section 13- Innovation and forward-looking methodology development | SP Transmission/SSENT | November 2022 |

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1.   INTRODUCTION

Risk is part of our everyday lives. In our everyday activities, such as crossing the road and driving our cars, we take risks. For these everyday activities, we often do not consciously evaluate the risks but we do take actions to reduce the chance of the risk materialising and/or the impact if it does.

Organisations are focussed on the effect risk can have on achieving their objectives e.g. keeping their staff, contractors and the public safe, providing an agreed level of service to their customers at an agreed price, protecting the environment, making a profit for shareholders.

Organisations manage risk by identifying it, analysing it and then evaluating whether the risk should and can be modified.

To help organisations to manage risks, the International Standards Organisation has produced ISO 31000:2009 Risk management - Principles and guidelines which includes several definitions, principles and guidelines associated with risk management which provide a basis for identifying risk, analysing risk and modifying risk. In addition, BS EN 60812:2006 (Analysis Techniques for System Reliability) provides useful guidance on analysis techniques for system reliability. In this methodology, we have utilised relevant content from ISO 55001, ISO 31000 and BS EN 60812.

Risk is often expressed in terms of a combination of the associated likelihood of an event (including changes in circumstances) and the consequences of the occurrence.

Likelihood can be defined, measured or determined objectively or subjectively, qualitatively or quantitatively, and described either using general terms or mathematically (such as a probability or a frequency over a given time-period).

Similarly, consequences can be certain or uncertain, can have positive and negative effects on objectives and can be expressed qualitatively or quantitatively.

A single event can lead to a range of consequences and initial consequences can escalate through knock-on effects.

The combination of likelihood and consequence is often expressed in a risk matrix where likelihood is placed on one axis and consequence on the other.

This combination is not necessarily mathematical as the matrix is often divided into categories on the rows and the columns and can be categorised in whatever form is applicable to the risks under consideration.

Sometimes this combination of likelihood and consequence is expressed mathematically as:

Equation 1

$$Risk\ =\ Likelihood\ x\ Consequence$$

In this mathematical form whilst it is necessary for the likelihood and consequence to be expressed numerically for such an equation to work, the likelihood does not necessarily have to be a probability and the consequence can be expressed in any numeric form.

When using, likelihood expressed as a probability and consequence expressed as a cost, using the risk equation provides a risk cost. This risk cost enables ranking of the risk compared with others risks calculated in the same manner. This is true for any risk expressed numerically on the same basis.

When considering the risk of a non-recurring single event over a defined time-period, the event has two expected outcomes, either it will occur resulting in up to the full consequence cost or it will not occur, resulting in a zero-consequence cost.

For this reason, the use of summated risk costs for financial provision over a defined time-period works best when there is a large collection of risks. This is because if only a small number of risks are being considered, a financial provision based on summated risk cost will either be larger or smaller than is required.

This is particularly the case for high-impact, low-probability (HILP) risks. It is generally unusual to have a large collection of HILP risks and so the summated risk cost does not give a good estimate of what financial provision is required. There are also particular considerations with respect to these risks when using risk cost to rank subsequent actions.

1.1. METHODOLOGY OVERVIEW

To ascertain the overall level of risk for each TO, the NARM methodology will calculate Asset Risk for lead assets only, namely:

1. Circuit Breakers
2. Transformers
3. Reactors
4. Underground Cable
5. Overhead Line Conductor
6. Overhead Line Fittings
7. Overhead Line Towers

 As shown in Equation 2, the Asset Risk is the sum of the expected values of each consequence associated with that asset and a function of the probability of each failure mode occurring.

For a given asset, a measure of the risk associated with it is the Asset Risk (AR), given by:

Equation 2

$$AR = \sum_{j=1}^{n} PoF_j \times CoF_j$$

where:

PoF_j = Probability of Failure *j* occurring during a given time
CoF_j = the monetised Consequence of Failure *j*
n = the number of Failures associated with Asset

For the network, a measure of the risk associated with it is the Network Risk (NR), given by:

Equation 3

$$NR = \sum_{k=1}^{n} AR_k$$

where:

AR_k = the Asset Risk associated with Asset, k.
n=the number of Assets on the Network

Consequence is the monetised value for each of the underlying Financial, Safety, System and Environmental components of a consequence e.g. Transformer Fire. A consequence can be caused by more than one Failure Mode, but a Consequence itself can only occur once during the next time-period. For example, an Asset or a component is only irreparably damaged once.

1.1.1. NARM ASSET (A)

An asset is defined as a unique instance of one of the above seven lead assets. Overhead Line and Cable routes will be broken down into the individual assets which are components of the route. Each asset has one or more Failure Mode Effects and a Failure Mode Effect can lead to one or more Consequences.

1.1.2. MATERIAL FAILURE MODE (F)

For reasons of economic efficiency, TOs do not consider every possible failure mode and consequence, only those which are materially significant. TOs' assessment of material significance is based upon their experience and consequential information set. TOs have different information sets and therefore have made different decisions, within the same overall methodology, about what should be measured or calculated from first principles and what must be estimated.

The material failure mode is a distinct way in which an asset or a component may fail. Fail means it no longer does what is designed to do and has a significant probability of causing a material consequence.

1.1.2.1. FAILURE MODE EFFECTS

There are many ways in which an Asset (A) can fail so to model the likelihood of an asset failure it is often more effective to consider the effect of the failure. Thus, historic data and the impact of observed condition data can be used to determine the probability of a Failure Mode's Effect.

This Failure Mode Effect is often based on a measurable consequence of the failure; for example, the asset may be impaired functionally by a measurable level or no longer operates for a measurable period.

Failure Mode Effect	Definition
Defect	Failure does not cause an unplanned outage however requires a repair that could require a planned outage to be undertaken.
Minor	Failure causes an unplanned outage, but the asset can be returned to service within 24 hours
Significant	Failure causes an unplanned outage; the asset can be repaired but remains out of service for more than 24 hours but less than 10 days
Major	Failure causes an unplanned outage which causes extensive damage. Where repairs are possible, the duration of the works will exceed 10 days, or the failure will result in the asset being replaced.

Table 1 Definition of Failure Mode Effects

Each failure mode (F_i) needs to be mapped to one or more consequences (CoF_j) and the conditional probability the consequence will manifest should the failure occur $PoF(CoF_j|F_i)$.

However, where failure modes and consequences have a one-to-one mapping, this function is not required, and the Probability of Failure is equal to the Probability of Consequence.

1.1.3. PROBABILITY OF FAILURE MODE

Probability of failure ($P(F_i)$) represents the probability that a Failure Mode Effect will occur in the next time-period. It is generated from an underlying parametric probability distribution or failure curve. The nature of this curve and its parameters are informed by a combination of TOs' asset data, Industry wide data from ITOMS and EPRI and mathematical models judged appropriate by experts in this field.

Each Asset has an 'End of Life Modifier' EoL_{Y0} score assigned to it based on several parameters detailed later in this document. This EoL_{Y0} score is then used to calculate the Probability of Failure for each Failure Mode Effect P(F).

In addition, a combined probability of failure for all potential Failure Mode Effects can be calculated. Detailed calculation steps are provided in the following sections and the individual TO's Licensee Specific Appendix where necessary.

1.1.4. CONSEQUENCE (C)

The monetised value for each of the underlying Financial, Safety, System and Environmental components of a Failure Mode (e.g. unplanned outage for 4 days). Each C_j has one or more F_j mapped to it.

These consequences are related to the characteristics of the Asset and its location, so the same Failure Mode for similar assets at different locations are likely to have different monetised values.

2.   END OF LIFE MODIFIER AND PROBABILITY OF FAILURE

The determination of Probability of Failure (PoF) can be especially challenging for highly reliable assets. BS EN 60812 provides useful guidance on how to develop an estimate for PoF using Failure Mode and Effects Analysis (FMEA) techniques.

Section 5.2.9 of BS EN 60812 recognises that it is very important to consider the operational profile (environmental, mechanical, and/or electrical stresses applied) of each component that contributes to its probability of occurrence. This is because the component failure rates, and consequently failure rate of the failure mode under consideration, in most cases increase proportionally with the increase of applied stresses with the power law relationship or exponentially. Probability of occurrence of the failure modes for the design can be estimated from:

•   Data from the component life testing

•   Available databases of failure rates

•   Field failure data

•   Failure data for similar items or for the component class

When probability of occurrence is estimated, the FMEA must specify the period over which the estimations are valid (such as the expected service life).

Section 5.3.4 of BS EN 60812 provides further guidance on the estimation of failure rates where measured data is not available for every asset and specific operation condition (as is generally the case for transmission assets). In this case, environmental, loading and maintenance conditions different from those relating to the "reference" failure rate data are accounted for by a modifying factor. Special care needs to be exercised to ensure that the chosen modifiers are correct and applicable for the specific system and its operating conditions.

It is recognised that each TO will have different asset profiles in different operating environments. Different operating regimes and historic maintenance practises will therefore result in different PoF outcomes. Furthermore, differences in recording and classification of historic performance data may mean that PoF rates are not directly comparable, and different methodologies may need to be employed to determine the asset PoF.

The failure modes and effects analysis define an end of life curve for each asset. It is recognised that some of these predicted deterioration mechanisms have yet to present themselves and were based on knowledge of asset design and specific research and development into deterioration mechanisms. In summary, the following sources of data were utilised:

•   Results of forensic evidence

•   Results of condition assessment tests

•   Results of continuous monitoring

•   Historical and projected environmental performance (e.g. oil loss)

•   Historical and projected unreliability

•   Defect history for that circuit breaker family.

This process uses asset-specific information; from both intrusive and non-intrusive inspections to derive a series of differentiators and modifiers which are then used to produce an overall End of Life Modifier. From that, the asset's failure mode frequency or Probability of Failure (PoF) is derived.

Asset management information is fed into the Process to produce a EoL Modifier for each asset, which is referred to as $EoL_{(Y0)}$. It is from this EoL Modifier that a probability of failure, (PoF), is calculated for several defined failure modes.

2.1. END OF LIFE MODIFIER

The present year EoL Modifier (EoL_{Y0}) of an asset is scored on a continuous scale between 0.5 and 10. The minimum value (EoL_{lim}) of 0.5 represents the point at which there starts to be a direct relationship between the End of Life modifier and an increasing PoF. Failures associated with modifiers below this limit relate to manufacturing/installation issues or random events. With the sharply rising EoL/PoF relationship it would be expected that End of Life will be when the EoL value reaches somewhere between 6 and 10. Typically, end of life is defined as EoL of 7 or greater.
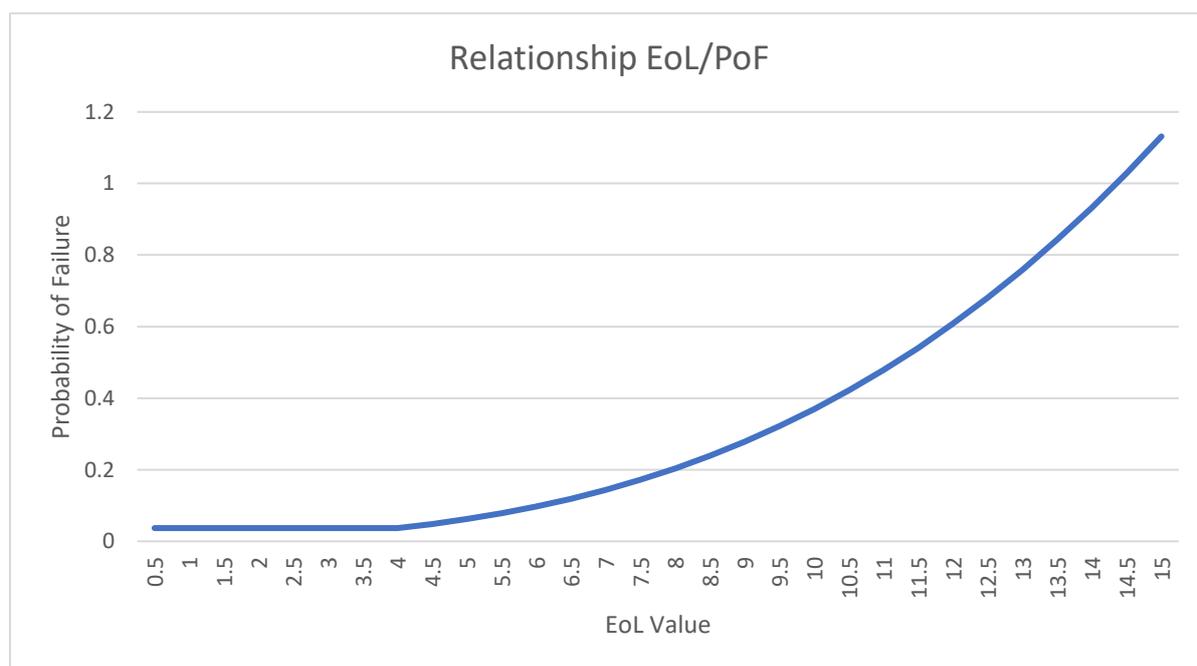
Figure 1 Relationship Between PoF and EoL

As outlined in Figure 1, the future EoL modifier (EoL_{yn}) can produce forecast scores up to 15. This is to help with the decision-making process for asset replacement strategies. When an asset needs direct replacement, the project is likely to include a development period of several years. With the End of Life value calculated past 10, it allows for the prediction of probability of failure in the future and differentiation between assets which may fail sooner than others.

Used by EoL Calculation														
Actual Asset Lifecycle										Theoretical Life for Decision Purposes				
Normal Operation					Material Deterioration			End of Life			Projected End of Life			
1	2	3	4	5	5.5	6	6.5	7	8	9	10	11	12	13	14	15

Table 2 Showing End of Life Values

The concept of the End of Life Modifier is used to embody all variables that may influence the probability of each failure mode both at the time of calculation and in the future. The detail of the End of Life Modifier calculation is different for each asset class, reflecting the different information and the different types of degradation processes. This calculation is described in Sections 0 to 6. There is, however, an underlying structure for all asset groups as outlined in Figure 2.
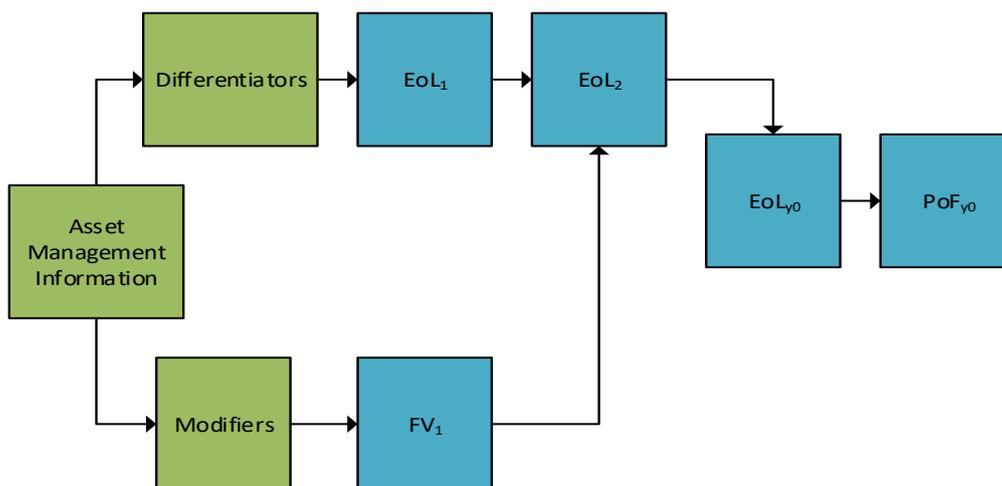
Figure 2 Process Overview

Where:

EoL$_1$ =   Initial End of Life Modifier

EoL$_2$ =   Intermediate End of Life Modifier

EoL$_{y0}$ =   Final End of Life Value

PoF$_{y0}$ =   Probability of failure for that year

FV$_1$ =   Conditional Factor Values for that asset.

2.1.1.   DIFFERENTIATORS AND MODIFIERS

2.1.1.1.   DIFFERENTIATORS

For a specific asset, an initial End of Life Modifier (EoL$_1$) is calculated using knowledge and experience of its performance and expected lifetime, taking account of differentiating factors such as original specification, manufacturer data, operational experience and operating conditions (duty, proximity to coast, etc.).

Differentiators are used to account for the different asset lifetimes that can be reasonably anticipated because of external differentiating factors. Examples of these differentiators may include:

- Duty (individually described within each asset section)
- Location specific reasons, such as proximity to coastal areas or heavily polluted industrial areas

2.1.1.2. MODIFIERS

Information that is indicative of condition is used to create additional 'factors' that modify the initial End of Life Modifier and form the Intermediate End of Life Modifier EoL_2. This includes information that cannot be directly related to specific degradation processes, such as factors relating to fault / defect history and reliability issues associated with specific equipment types (e.g. different manufacturers). It also includes information related to specific degradation processes that identify potential end of life conditions (e.g. corrosion), but is not generally considered sufficient to provide a definitive indication of asset condition independently of other information. Whilst this information is not used to provide a specific End of Life value, it can be used to define a minimum value for the asset and a boundary value for the modifiers (See Section 2.2.2   Intermediate   EoL   Modifier (EoL2).

Where condition information related to specific degradation process can be used to identify end of life conditions with a high degree of confidence (e.g. dissolved gas analysis of transformer oil provides a high confidence indication of the health of the transformer regardless of other information available), this is used to directly derive an End of Life Value for the asset via the Specific Degradation Process Modifier. This could include condition information derived from specific tests or very detailed visual condition information obtained from helicopter inspections of overhead lines. Where appropriate, the values derived from such tests can be used in preference to the Intermediate based End of Life Modifier described above.

Within this Process, these modifiers include:

- Visual Condition
- Defects
- Generic Reliability
- Test Results
- Operational restrictions

Each asset will have its own suite of modifiers; these are described in more detail in the asset specific sections. Additionally, any modifiers which are Company Specific will also be described within the Licensee Specific Appendices.

Visual External Condition Factors

The observed external condition of the asset is evaluated through visual assessment by operational staff. Several components are assessed individually and assigned a condition. Each component's condition is weighted differently based on the significance of the component. These components are combined to produce an overall scale and a Condition factor is produced.

Defects

A defect is a fault on an asset which does not cause the asset to be removed from service and can be repaired. Each defect has a severity score against it and the combination of those values generates a Defect factor. with each asset.

Generic Reliability

Generic Reliability is determined using the TO's own experience of assets in operation and external information where applicable. Each asset family is assigned a reliability rating (e.g. from 1-4, with 1 being Very Reliable and 4 being Very Unreliable) which then generates a reliability factor.

Test Results

Where tests have been undertaken, the results (e.g. pass, suspect or fail) for each test type are used to derive individual test factors (and if desired minimum EoL Modifier) and are then combined to produce an overall test factor.

Operational Restrictions

When a significant issue is identified regarding an asset family, a Transmission Owner (TO) can issue a NEDeR[1] which notifies all other TOs. This is called an Operational Restriction, or "OR". Each OR is assigned a severity, which then generates an Operational Restriction factor.

For assets, which have more than one OR assigned to them, it is the largest factor (or most serious OR) which is passed through to form the overall OR factor.

2.1.2. INITIAL EOL MODIFIER (EOL$_1$)

The Initial EoL Modifier EoL$_1$ is based around the age of an asset in relation to the estimated average expected service life which could be reasonably anticipated. This calculation stage does consider the expected life of the asset, coupled with its workload in operation, its situation (indoor / outdoor), location (proximity to coast, elevation, corrosion factor) and the environment. It does not however at this point consider condition, testing or defect intervention.   The first stage of the derivation is described below in Figure 3.

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[1] Notification to the Energy Networks Association's National Equipment Defect Reporting Scheme
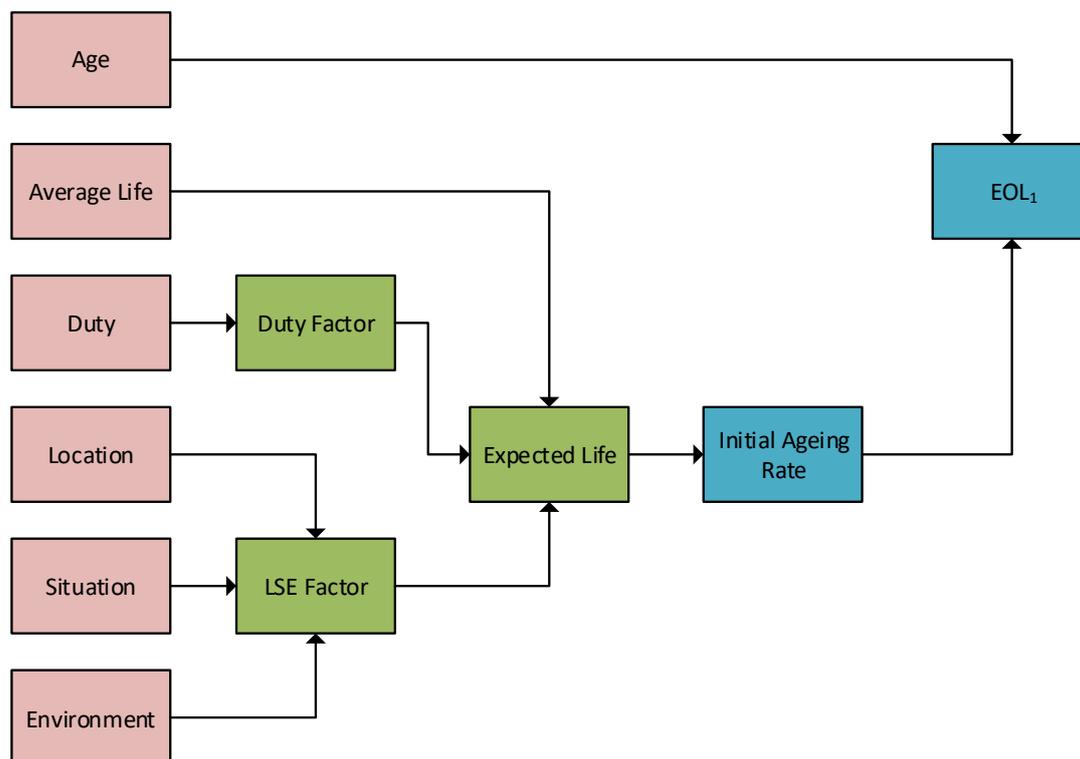
Figure 3 Derivation of Initial End of Life Modifier

Using a logarithmic function, an initial ageing rate (initial because condition information is not considered) can be mapped out.

Finally, the Initial Ageing rate combined with the asset's age and the EoL of a new asset in an exponential function determines the Initial End of Life value of that asset.

The Initial Indicator is capped at a value of 5.5 to reflect the fact that age alone should not be sufficient to indicate that an asset has reached end of life; EoL can only be achieved when there is condition related information indicating significant degradation.

It should be noted that the derivation of all factors is TO specific and subject to calibration, testing and validation during the implementation of the methodology within the individual TOs.

2.1.2.1.   DUTY FACTOR

One of the variables required when calculating the Expected Life of an asset is its applied duty. The Duty Factor is asset specific in its determination and TO specific to the variables used to find the overall Duty Factor. It should be noted that neutral default Duty Factor values are applied to asset categories where no duty factors have been identified. This is also the case where the relevant data/information is not available to calculate the Duty Factor. More information on the Duty Factor can be discerned in the Asset Specific Sections, starting at Section 0.

2.1.2.2.   LSE FACTOR (LOCATION, SITUATION, ENVIRONMENT)

The Expected Life of an asset is affected by the environment in which the asset is installed. The LSE factor is generally calculated from the following variables:

- Distance to coast
- Altitude
- Corrosion rating
- Situation (indoor/outdoor)
- Environment

For above ground assets the location factor is calculated from the distance to coast, altitude, and corrosion zone variables, the Situation Factor indicates whether the asset is situated indoors or outdoors and the Environment Factor represents the severity of the local environment. Cables and tower foundations use additional specific variables which are described in more detail in the relevant sections.

More information on the calculation of the LSE Factor can be discerned in the Asset Specific Sections, starting at Section 3.

Details on the possible values assigned to these variables and the derivation of the LSE factor per each lead asset can be found in the respective TO's Licensee Specific Appendices.

2.1.2.3.   EXPECTED LIFE

Starting with the Expected Average Life (L_A) for that asset class, the Duty and LSE factors are used to set an expected life (L_E) for each asset.

Equation 4

$$L_E = \frac{L_A}{F_{LSE} \times F_{DY}}$$

Where;

F_{LSE} =   LSE Factor
F_{DY} =   Duty Factor

This expected life is then used to determine the Initial end of life Modifier EoL_1.

The Expected Asset Life is the time (in years) in an asset's life when it would be expected to reach deterioration that it is likely to exhibit functional failure. The determination of the L_A considers factors such as original specification and manufacturer data. This corresponds to a EoL Modifier of 7.

2.2.   THE AGEING MECHANISM

The model contains an ageing mechanism, which attempts to estimate the likely future EoL Modifier for each asset, referred to as EoL_{yn}, which is used to project the future PoF of each asset being considered. The rate of

change of the EoL Modifier is non-linear. The degradation processes involved (e.g., corrosion) are accelerated by the products of the process, hence the rate of deterioration increases as the processes proceed.

Section 5.2.9 of BS EN 60812-2006 provides some guidance on the determination of this relationship:

"…besides published information regarding the failure rate, it is very important to consider the operational profile (environmental, mechanical, and/or electrical stresses applied) of each component that contribute to its probability of occurrence. This is because the component failure rates, and consequently failure rate of the failure mode under consideration, in most cases increase proportionally with the increase of applied stresses with the power law relationship or exponentially."

Although the standard recommends that failure rates should be derived from field failure data, there is little useful published data on electrical asset failure rates, especially at transmission level.

Nevertheless, most Transmission Owners have many years of experience of asset operation and so it is this experience and historical data that is used primarily to determine this relationship. Through the electricity industry's Strategic Technology Programme, it was observed that electrical asset failure rates correlated with asset health according to a semi-Markov relationship[2], leading to an exponential function that for a given asset, explained in Equation 5:

Equation 5

$$EoL_{t2} = EoL_{t1} \cdot \exp\{\beta \cdot (t_2 - t_1)\}$$

where:

EoL_{t2}	=	EoL Modifier at time t_2
EoL_{t1}	=	EoL Modifier at time t_1
β	=	Ageing rate
$(t_2 - t_1)$	=	Time taken for the asset to move from EoL_{t1} to EoL_{t2}

The Initial EOL Indicator of each asset is derived using its Initial Ageing Rate (Section 2.2.1 for further details) and its current age (this corresponds to the time taken for the asset to move from the Indicator of a new asset to its Initial Indicator) by the making the following substitutions into Equation 6:

Equation 6

$$EoL_{1,i} = EoL_{New} \cdot \exp\{\beta_{1,i} \cdot Age_i\}$$

where:

$EoL_{1,i}$ = Initial EOL Indicator of asset i

EOL_{New} = Indicator of a new asset (normally set to 0.5)

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[2] "Using Modelling to Understand and Improve CBRM" STP project reference 4167, AT Brint, JR Brailsford and D Hughes (2006).

$\beta_{1,i}$ =   Initial Ageing Rate of asset i (Section 2.2.1)

The Initial Indicator is capped at a value of 5.5 to reflect the fact that age alone should not be sufficient to indicate that an asset has reached end of life; EoL can only be achieved when there is condition related information indicating significant degradation[3].

The methodology also calculates an 'initial ageing rate', 'b', for each asset which is used as an input to the ageing mechanism outlined below which is employed for any future asset EoL Modifier estimation. The standard EoL$_{(y0)}$ calculates the number of years it will take each asset to reach a EoL of 10, the EoL Modifier which is defined as the "end of life".

2.2.1.   INITIAL AGEING RATE

The Initial Ageing Rate is needed to determine the rate of change of the EoL Modifier. The standard approach adopted is to estimate the time for the EoL Modifier to move from 0.5 (i.e. a new asset) to 5.5 (the end of an asset's anticipated life and the point at which the probability of failure starts to rise significantly (see Section 2.1 for further details). The time (t2 – t1) in Equation 5 is the expected life of the asset as defined in Section 2.1.2.3

The Modified Expected Life of an asset varies depending both on the asset type and its operating conditions. Therefore, a different value must be calculated for each individual asset based on its Modified Anticipated Life, using Equation 7.

Equation 7

$$B_i = \ln\left(\frac{\text{EoL}_{MAL}}{EOL_{New}}\right) \cdot \frac{1}{L_E}$$

where:

EoL_{MAL} =   EoL Modifier of the asset when it reaches its Modified Anticipated Life (set to 5.5)
EOL_{New} =   EoL Modifier of a new asset (normally set to 0.5)
L_E =   Expected Asset Life, i (as determined using Section 2.1.2.3)

2.2.2.   INTERMEDIATE EOL MODIFIER (EOL2)

The second calculation stage, i.e. to find EoL$_2$, introduces more specific asset information pertaining to observed condition, inspection surveys, maintenance test results and the TO's experience of each asset. Some typical modifiers, including EoL$_1$ from the previous stage, are shown in Figure 4 Intermediate End of Life modifier derivation below.

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[3] This only applies in year 0; EoL can be achieved in future years when there is no condition information.
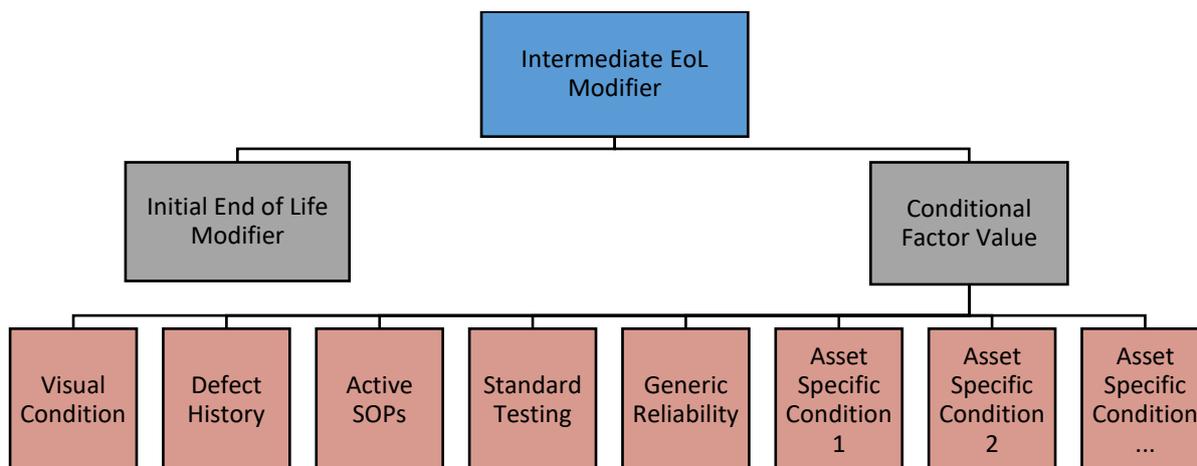
Figure 4 Intermediate End of Life modifier derivation

Condition factors are determined by specific asset information pertaining to;

•   Observed condition
•   Inspection surveys
•   Maintenance test results
•   TO's experience of each asset
•   Reliability inputs

These are combined with respect to their individual weightings in a function known as Maximum and Multiple Increment Methodology.

Modifiers specific to each asset type are identified in asset specific modifiers Section 0 onwards.

The initial end of life modifier does not take into consideration any of the measured asset's conditional factors. To calculate an Intermediate End of Life modifier, the initial end of life modifier is simply multiplied by a conditional factor value.

Equation 8

$$EoL_2 = EoL_1 \times FV_1$$

Where condition information related to specific degradation process can be used to identify end of life conditions with a high degree of confidence (e.g. dissolved gas analysis of transformer oil provides an indication of the health of the transformer regardless of other information available), this is used to directly derive an End of Life Indicator for the asset. This could include condition information derived from specific tests or very detailed visual condition information obtained from aerial inspections of overhead lines. Where appropriate, the values derived from such tests can be used in preference to the modified age-based End of Life Indicator described above. Modifiers specific to each asset type are identified in Sections 0 to 6.

2.2.2.1. MAXIMUM AND MULTIPLE INCREMENT (MMI) METHODOLOGY

This MMI methodology is used to combine multiple factors into a single value that ensures the Intermediate End of Life Modifier is primarily driven by the strongest observed factor.

Whilst multiple factors may be considered in the derivation of a single combined factor using the MMI Technique there will be instances where not all of the multiple factors affect the resulting factor. These conditions are expanded further below.

FV_1 is calculated in one of two ways, depending on the value of the factors being combined. If any of the factors are greater than the condition max divider value:

Equation 9

$$FV_1 = \text{largest factor} + \frac{\sum_{i=1}^{n}((n+1)th\ largest\ factor - 1)}{Condition\ Max\ Divider}\ where\ (n+1)th\ largest\ factor \\ > Condition\ Max\ Boundary$$

And, if none of the factors are greater than the condition max divider value:

Equation 10

$$FV_1 = Smallest\ Factor + \frac{Second\ Smallest\ Factor - 1}{Condition\ Min\ Divider}$$

The Condition Min divider, Condition Max divider and Condition Max Boundary factors are specific per each MMI calculation throughout the Methodology calculation and as specified as calibration values in respective Licensee Specific Appendices.

2.2.3. END OF LIFE VALUE (EOL$_{Y0}$)

The end of life value EoL_{y0}, is asset class specific and explained in the relevant sections.

In general, the EoL_{y0} is taken as the maximum of the Intermediate End of Life Modifier (EoL_2), any asset specific modifiers and the largest of the calibratable minimum forced End of Life modifiers.

2.2.3.1. MINIMUM END OF LIFE MODIFIERS

A series of calibratable minimum forced End of Modifiers are employed. These overrides serve to force the End of Life Modifier to a calibrated minimum value which is consistent with its observed or measured levels of deterioration. Minimum End of Life Modifiers are applied to each of the factors utilised in the derivation of the Intermediate End of Life Modifier. The maximum of these minimum End of Life Modifiers (known as the maximum of the minimums) is taken forward to derive an assets final End of Life Value. Details of the minimum End of Life Modifiers can be found in the Licensee Specific Appendices for each lead asset.

2.3. FORECASTING END OF LIFE

We determine the EoL Modifier in future years using the following

Equation 11

$$EoL_{y(n)} = EoL_{y(0)} e^{b\Delta T}$$

Where:

ΔT = time between years 0 and n.

This is initially determined using the expected life of the asset as ΔT, and the maximum and minimum EoL$_S$ as EoL$_{(yn)}$ and EoL$_{(y0)}$ respectively. With all other variables known, b can then be calculated.

On an individual asset basis, the methodology firstly considers each asset's age to determine whether an ageing rate reduction factor should be included in the future EoL Modifier estimation calculation. For example, where an asset has reached near to end-of-life with no indications of problems, it is more likely to live longer than initially expected and so the ageing rate reduction factor should be included.

Once this has been determined, all the information is available to produce a future EoL Modifier. Having made this estimation for each of the subcomponent parts of the larger system, the Process re-combines the EoL Modifier to produce an estimated future system EoL Modifier for each asset.

The information above can also be used to determine an approximate rate of deterioration and, therefore, to estimate future asset EoL Modifier, which can be seen in **Error! Reference source not found.** below.
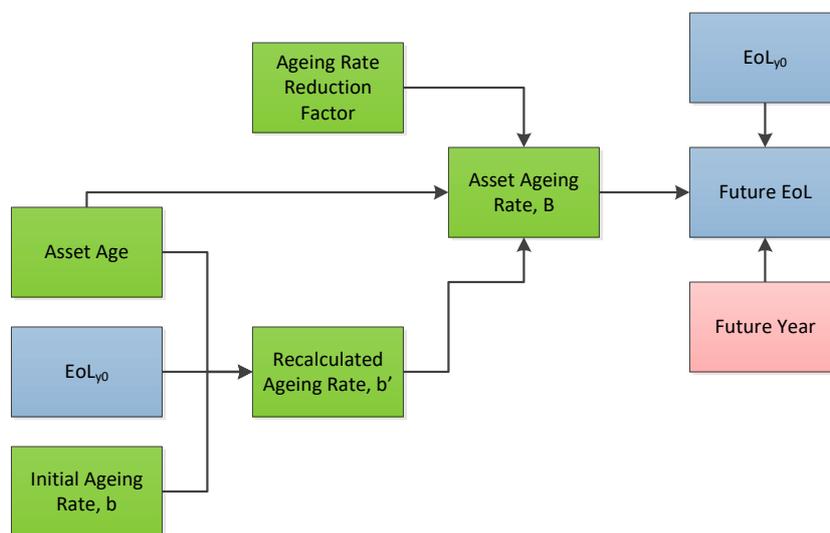
Figure 5 Forecasting Probability of Failure

The current EoL Modifier profile of a group of assets provides a 'snapshot' of the current condition of those assets. It is also possible through the application of **Error! Reference source not found.** to predict how these assets will behave in the future; i.e. how the EoL Modifier will change going forwards. To do so, it is first

24

necessary to determine the Final Ageing Rate and the Ageing Reduction Factor for the asset. Once these are known, EoL Modifier for any asset in any future year t_{YN}, can be calculated as follows:

Equation 12

$$\mathrm{EoL}_{Yn,1} = \mathrm{maximum}\left(\mathrm{EoL}_{Y0,i} \cdot \exp\left\{\frac{\beta_{final,i} \cdot (t_{YN} - t_{Y0})}{F_{age,i}}\right\}, EOL_{YN,max}\right)$$

where:

$\mathrm{EoL}_{YN,i}$ = EoL Modifier of asset i in future year Y_N

$\beta_{final,i}$ = Final Ageing Rate of asset i

$F_{age,i}$ = Ageing Reduction Factor for asset i

$(t_{YN} - t_{Y0})$ = Number of years over which the asset moves from $\mathrm{EoL}_{Y0,i}$ to $\mathrm{EoL}_{YN,i}$

$\mathrm{EoL}_{YN,max}$ = Maximum allowable value for the Future Indicator; typically set to 15.

Where an Indicator is derived for multiple sub-components, the Future Indicator is derived by ageing each component to derive the EoL Modifier of the individual sub-components in the future year; these are then re-combined to produce the future overall EoL Modifier.

2.3.1.   FINAL AGEING RATE

For assets that are new and/or in good condition, the EoL Modifier is determined using the Initial Ageing Rate. This prevents very slow ageing of an asset due to very good condition results, which would otherwise result in an unrealistic time for the asset to reach its end of life.

These assets are identified as those with a EoL Modifier below a defined threshold or those younger than a defined age limit. **Error! Reference source not found.** is used to calculate final ageing rate, as below:

Equation 13

$$\text{Thus, when; } Age_i < Age_{recalc} \text{ or } \mathrm{EoL}_{Y0,i} \leq \mathrm{EoL}_{recalc}$$

$$\beta_{final,i} = \beta_{1,i}$$

where:

$\beta_{1,I}$ = Initial Aging Rate
Age_i = Current age of asset i
Age_{recalc} = Age limit for recalculating the ageing rate
EoL_{recalc} = Maximum EoL Modifier for using the Initial Ageing Rate

For other assets, the Final Ageing Rate is determined using the asset's EoL Modifier, as shown in **Error! Reference source not found.**:

Equation 14

$$\beta_{final,i} = maximum \left[\frac{\ln\left(\frac{HI_{Y0}}{HI_{New}}\right)}{Age_i}, \beta_{1,i}.\beta_{ratio} \right]$$

where:

β_{ratio} =   Maximum ratio between the Final Ageing Rate and the Initial Ageing Rate.

The ratio between the Initial Ageing Rate and the Final Ageing Rate is limited to prevent very rapid ageing of an asset due to very poor condition results or reliability issues that would otherwise result in an unrealistic time for the asset to reach its end of life. The maximum ratio is a calibration value and is typically set to a value of 2.

2.3.2. AGEING REDUCTION FACTOR

The Ageing Reduction Factor accounts for the increased life expectancy of an asset as it grows older; i.e. it slows the ageing process for assets that have started to age. This is necessary to model the effect of scheduling increasingly intensive or frequent maintenance as an asset approaches the end of its life. The relationship between EoL Modifier and the Ageing Reduction Factor is shown in **Error! Reference source not found.**.
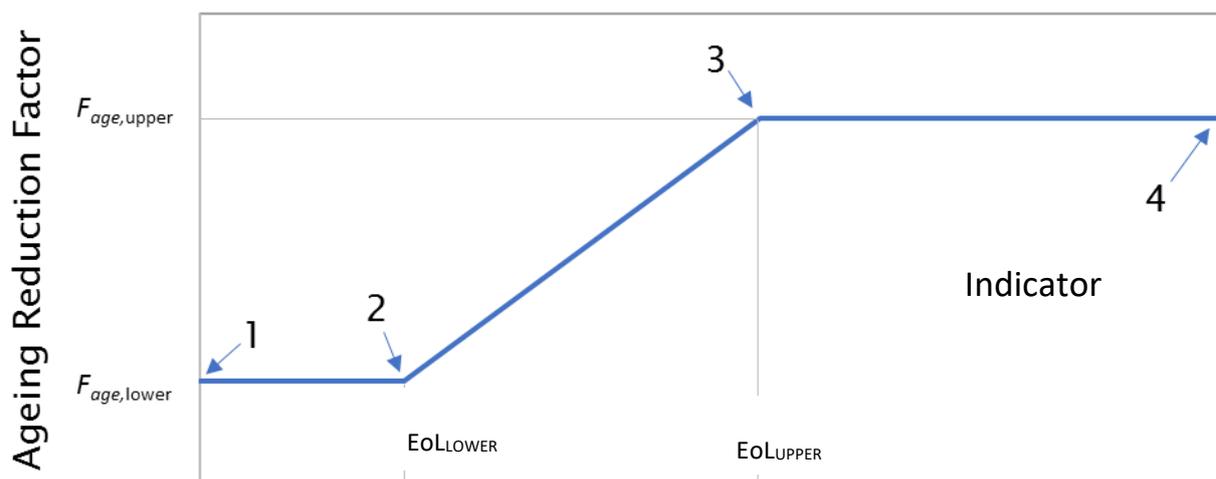
Figure 6 Ageing Rate Reduction Factor

where:

$F_{age,lower}$ =   Lower threshold for the Aging Reduction Factor
$F_{age,upper}$ =   Upper threshold for the Ageing Reduction Factor
EoL_{lower} =   Value of Indicator below which the lower threshold for the Ageing Reduction Factor is used
EoL_{upper} =   Value of Indicator above which the upper threshold for the Ageing Reduction Factor is used

If the EoL Modifier of the asset is between EoL_{lower} and EoL_{upper}, the Ageing Reduction Factor varies linearly as described by **Error! Reference source not found.**

Equation 15

$$F_{age} = F_{age,lower} + \left(\frac{EoL_{Y0} - EoL_{lower}}{EoL_{upper} - EoL_{lower}} \right) . \left(F_{age,upper} - F_{age,lower} \right)$$

The relationship between EoL Modifier and Ageing Reduction Factor is set via a calibration table which defines points 1 to 4 shown in **Error! Reference source not found.**. The values used to define the Ageing Reduction Factor in all the models were determined empirically from historical records and are shown below.

Point	EoL Modifier	Aging Rate Reduction Factor
1	0.5	1.0
2	2.0	1.0
3	5.5	1.5
4	15	1.5

Table 3 Ageing Reduction Factor Calibration Values

The failure effect frequency directly maps to the failure mode frequency, due to the way that the failure effects and failure modes have been categorised.

3. EOL CALCULATION FOR CIRCUIT BREAKERS

The following sections of this document provide an overview of the Circuit Breaker model design.

For each stage in the EoL Value derivation, the overview will identify and name all the component parts of each derivation and provide a high-level explanation of what the component parts represent.

3.1. INITIAL END OF LIFE MODIFIER

The Circuit Breaker Initial End of Life Modifier is calculated per Section 2.1.2. Variables to consider with Circuit Breakers are described below.

3.1.1. DUTY FACTOR

For each circuit breaker, the duty factor is calculated per the data available to the TO to make the best analysis of an assets utilisation.

- Presence of feeder protection (Prot), as the duty factor will be higher where this is present.
- Presence of Auto-Reclose (R_A), as the duty factor will be higher where this is present.
- Operational experience in the form of a 'high duty' exception report (D_H).
- The fault current the circuit breaker clears during its life (DI^2t) is used to calculate the Duty Override Factor (F_{DY})
- Fault Level compared to Fault Rating, as the duty factor should be higher where the fault level exceeds the rating (D_{FAULT}).
- Latest record of the total number of Fault Clearances undertaken by the circuit breaker. (D_{CLEAR}).

The combination of these three variables determines an overall duty factor using the following equation:

Equation 16 Duty Factor Calculation for circuit Breakers SSENT

$$F_{DY} = max(Prot, R_A, D_H)$$

Equation 17 Duty Factor Calculation for Circuit Breakers SPT

$$F_{DY} = DI^2t$$

Or if I^2t not available,

$$F_{DY} = D_{Fault} \cdot D_{Clear}$$

3.1.2. LSE FACTOR

The circuit breaker Initial End of Life Modifier is calculated in Section 3.1.4 where the LSE Factor is calculated as:

Equation 18

Internal Use

$$LSE\ Factor = (((Location\ Factor - Minimum\ Location\ Factor) \times Situation\ Factor)$$
$$+ Minimum\ Location\ Factor) \times Environment\ Factor$$

Where the Location Factor, F_{loc} is then derived by combining the Distance to Coast, Altitude and Corrosion values factors as follows:

Equation 19

$$F_{loc} = max(F_{dis}, F_{alt}, F_{cor})$$

Minimum Location Factor, $F_{loc,min}$ is the minimum possible location factor and is set by a calibration value, defined in the TO's Licensee Specific Appendix.

Distance to Coast, Altitude and Corrosion Factor values are derived via calibration tables in the respective TO's Licensee Specific Appendices.

3.1.3. EXPECTED LIFE

Starting with the Expected Average Life (L_A), the Duty and LSE factors are used to set an expected life (L_E) for each asset.

Equation 20

$$L_E = \frac{L_A}{F_{LSE} \times F_{DY}}$$

This expected life is then used to determine EoL_1.

The Expected Asset Life is the time (in years) in an asset's life when it would be expected to such deterioration that it is likely to exhibit functional failure. The determination of the L_A considers factors such as original specification and manufacturer data. This corresponds to an EoL Modifier of 5.5.

3.1.4. EOL1 CALCULATION

The initial EOL modifier is calculated as:

Equation 21

$$EoL_1 = min\ ((EoL_{New} \cdot exp\{\beta_1 \cdot Age\}), EoL_{1,max})$$

Where:

$EOL_{1,\ max}$ is 5.5

And $EoL_{1,i}$ is the Initial Indicator of asset I calculated as:

Equation 22

$$EoL_{1,i} = EoL_{New} \cdot exp\{\beta_{1,i} \cdot Age_i\}$$

where:

$EoL_{1,i}$ = Initial Indicator of asset i

EOL_{New} = Indicator of a new asset (normally set to 0.5)

$\beta_{1,i}$ = Initial Ageing Rate of asset i (Section 2.2.1)

3.2.   INTERMEDIATE EOL MODIFIER (EOL$_2$)

The circuit breaker intermediate end of life modifier is calculated for Factors:

- Visual Condition
- Defects
- Generic Reliability
- Test Results
- Operational restrictions

Additional Factors that can be included in the calculation of FV_1 are:

- Oil Condition
- AFM Score
- SF_6 Condition and
- SF_6 Leak factors, as shown in the Figure 7 below.

The parameters used in the derivation of the overall factor value using the "Maximum and Multiple Increment" combination method, as set out Section 2.2.2.1, are provided in the licensee specific appendices.
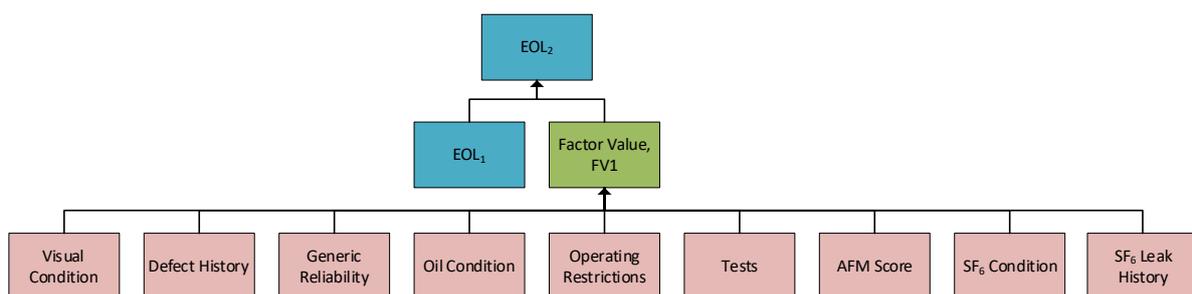
Figure 7 EoL Calculation for Circuit Breakers

Visual Condition

The observed condition of the circuit breaker is evaluated through visual assessment by operational staff. Several components of the circuit breaker are assessed individually and assigned a condition. Condition is assessed on a 1-5 scale for SPT (1 = new or as new, 5 = intervention required) and a 1-4 scale for SSENT (1 = new or as new, 4 = intervention required). Each component's condition is weighted differently, based on the significance of the component, to create a factor and a minimum EoL.

Internal Use

Each TO's License Specific Appendix provides the calibration values associated with each score.

The condition factors are combined using the "Maximum and Multiple Increment" combination method to determine the Overall Condition Factor. The Overall Condition Minimum EoL is the maximum of the individual condition minimum EoLs.

Defect History

Defect history provides a useful way of identifying assets that are approaching the point at which the probability of failure is starting to increase. An asset that has experienced a high number of defects would be expected to have a higher End of Life Indicator than an otherwise similar asset which has not experienced any defects, even after the defects have been repaired.

Each of the recorded circuit breaker defects from the past 5 years is assigned a severity score. The severity scores are summed, and the total score is used to derive the Defect History Factor and minimum EoL. Each TO's License Specific Appendix provides the calibration values associated with each score.

Generic Reliability

Reliability of specific groups or families of assets is determined using experience of assets in operation. A reliability rating (from 1-4, with 1 being Very Reliable and 4 being Very Unreliable) is assigned on the basis of manufacturer and model. The reliability rating is then linked to a Generic Reliability Factor and a minimum EoL value via calibration tables as shown the respective TO's License Specific Appendices.

Test

The methodology allows for a number of different tests to be considered within the model. Those can be test such as Partial Discharge, timing test and ductor tests. The calibration values required to create a test factor and associated minimum EOL are shown in the respective TO's License Specific Appendices.

Operational Restrictions

When a significant issue is identified regarding a family of circuit breakers, an Operator can issue a NEDER which notifies all other operators. This is called an Operational Restriction (OR). Each OR is assigned a severity, which then generates an Operational Restriction Factor and a minimum EoL via calibration tables as shown in in the respective TO's License Specific Appendices.

Oil Condition

The oil condition factor considers the latest oil condition tests (moisture, acidity and breakdown strength), each of which is used to create a test score using the standard calibration values shown in the respective TO's License Specific Appendices.

After Fault Maintenance (AFM)

For assets which have after fault maintenance (AFM) scores, (i.e. assets whose arc extinguishing medium is either vacuum or SF_6), the AFM Score considers the rate of change of each asset's AFM score to estimate an "extrapolated life". This estimation is used to determine an AFM factor which is used within the "FV_1" derivation.

SF_6 Condition

Gas SF_6 condition results (e.g. moisture, purity, dew point etc) use a series of defined multipliers to derive separate gas condition scores. The sum of the gas condition scores is then used to determine an overall gas

condition factor (SF_{6COND}) used in the creation of modifying factor "FV_1", and an optional minimum EoL Modifier can be set where poor gas condition is detected, which is set aside for later in the process. The gas condition is only considered for a limited rolling time basis, as set in the LSA.

Equation 23

$$SF_{6\_COND} = sum \left(\left(HF_s \times HF_{multiplier} \right) + \left(SO_{2\_s} \times SO_{2\_multiplier} \right) + \left(SF_{6\_s} \times SF_{6\_multiplier} \right) \right.$$
$$\left. + \left(Dew\ Point_s \times Dew\ Point_{multiplier} \right) + \left(Purity_s \times Purity_{multiplier} \right) \right)$$

Where:

SF_{6_COND} = The overall SF_6 Condition factor
HF_s = Hydrogen Fluoride score
$HF_{multiplier}$ = Hydrogen Fluoride multiplier
SO_{2_s} = Sulphur Dioxide score
$SO_{2\_multiplier}$ = Sulphur Dioxide multiplier
SF_{6_s} = SF_6 moisture score
$SF_{6\_multiplier}$ = SF_6 moisture multiplier
$Dew\ Point_s$ = Dew Point score
$Dew\ Point_{multiplier}$ = Dew Point multiplier
$Purity_s$ = Purity score
$Purity_{multiplier}$ = Purity multiplier

The Licensee Specific Appendices expands further each TO's own implementation of SF_6 Condition.

Gas Leaks

Leakage of gas from a circuit breaker is indicative of reduced integrity of the breaker itself. The leakage history is used to create two different factors:

- SF_{6_NO}, determined by the number of times an asset has been topped up with SF_6,
- $SF6_{6\_LOST}$ a second factor which considers the mass of gas replaced in relation to the design weight of SF_6.

A third factor, SF_{6_HIST}, can be derived from poor leakage history exception report information which reflects the TO's experience of loss of SF_6 containment. The maximum of these factors is carried forward to be included in the EoL_2 calculation in **Error! Reference source not found.**.

Gas leaks are only considered for a limited rolling time basis, as set in the LSA.

Equation 24

$$SF_{6\_LEAK} = max\left(SF_{6\_NO}, SF_{6\_LOST}, SF_{6\_HIST} \right)$$

The Licensee Specific Appendices expands further each TO's own implementation of SF_6 Leakage.

Overall Factor value FV1

The condition factors are combined using the "Maximum and Multiple Increment" combination method to determine the Overall Condition Factor. The Overall Condition Minimum EoL is the maximum of the individual condition minimum EoLs. The calibration values required to apply the method can be found in each TO respective Licensee Specific Appendix

3.2.1. CALCULATION OF EOL MODIFIER (EOL$_2$)

To calculate an Intermediate End of Life modifier, the initial end of life modifier is simply multiplied by a conditional factor value.

Equation 25

$$EoL_2 = EoL_1 \times FV_1$$

3.3.   END OF LIFE MODIFIER

The derivation of the Current End of Life Indicator can be depicted as shown in Figure 8 below
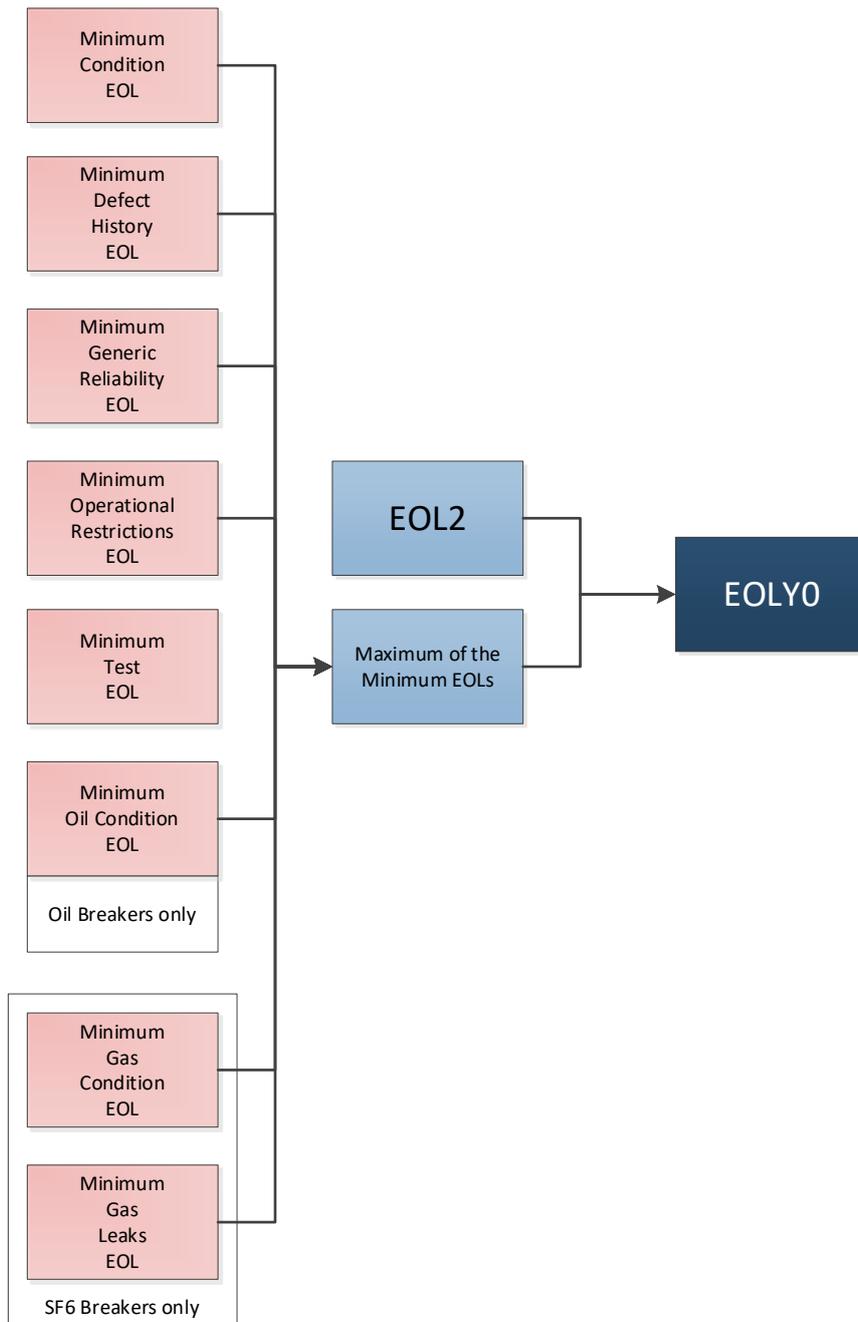
Figure 8 Derivation of Current End of Life Indicator, EoLY0 for Circuit Breaker

The circuit breaker end of life modifier is calculated as shown below:

Equation 26

$$EoL_{y0} = Max(EoL_2, Maximum\ of\ the\ Minimums)$$

4. EOL CALCULATION FOR TRANSFORMERS & REACTORS

Transformers and reactors are assigned an EoL Value (EoL) per their known condition and the service history of other similar transformers. Within this process, transmission transformers are considered as 'systems' which are made up of two components; a main tank (T_X), and a tapchanger (T_C). Each component is an individual asset, with a clearly defined linkage.

Failures involving multi-component systems such as the transformer system under consideration may be regarded as completely interdependent, and therefore links in a 'system chain'. This is the underlying principle behind the derivation of the final present day transformer system EoL Value EoL_{y0} (See Equation 27, which is generated from the larger of the transformer EoL_{y0} and its associated tapchanger EoL_{y0}.
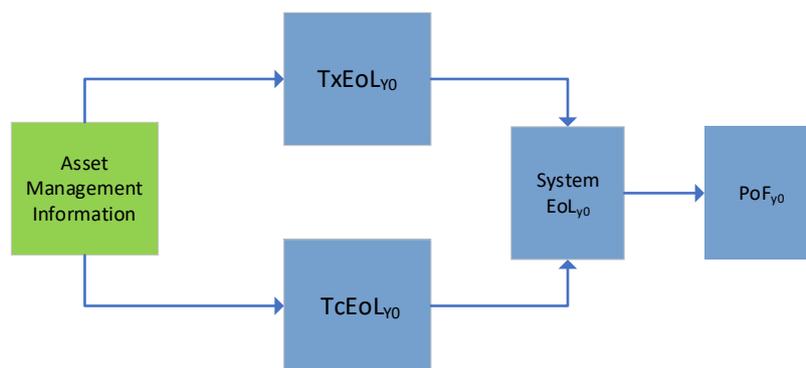
Figure 9 PoF Calculation for Transformers and Reactors

The Transformer System EoL indicator is defined as follows:

Equation 27

$$TxSystemEoL_{(y0)} = max\left(TxEoL_{(y0)}, TcEoL_{(y0)}\right)$$

Derivation of $TxEoL_{Y0}$ and $TcEoL_{Y0}$ is described in the following sections.

4.1. MAIN TANK (TX)

4.1.1. INITIAL END OF LIFE MODIFIER

The Transformer Initial End of Life Modifier is calculated per Section 2.1.2. Factors specific to Transformers are described below:

4.1.1.1. DUTY FACTOR

Duty Factor for each Transformer, the duty factor is calculated according to the data available to the TO to make the best analysis of an asset's utilisation.

- Maximum operating temperature recorded against each transformer, T_{max}. SHE Transmission use this variable instead of average demand.
- Maximum demand placed upon the transformer as a percentage of its stated rating, D_{max},
- Average demand placed upon the transformer as a percentage of its stated rating, D_{ave}
- Severity or Frequency of Through Faults, T_F

The combination of these variables determines an overall duty factor using either Equation 28 Duty Factor Calculation for Transformers or Equation 29 Duty Factor Calculation for Transformers SPT depending on the TO.

Equation 28 Duty Factor Calculation for Transformers SSENT

$$F_{DY} = max(T_{max}, D_{max}) * T_F$$

Equation 29 Duty Factor Calculation for Transformers SPT

$$F_{DY} = max(D_{max}, D_{ave})$$

4.1.1.2. LSE FACTOR

The Transformer Initial End of Life Modifier is calculated per Section 2.1.2.2 where the LSE Factor is calculated as:

Equation 30

$$LSE\ Factor = (((Location\ Factor - Minimum\ Location\ Factor) \times Situation\ Factor) \\ + Minimum\ Location\ Factor) \times Environment\ Factor$$

Where the Location Factor, F_{loc} is then derived by combining the Distance to Coast, Altitude and Corrosion values factors as follows:

Equation 31

$$F_{loc} = max(F_{dis}, F_{alt}, F_{cor})$$

Minimum Location Factor, $F_{loc,min}$ is set by a calibration value, defined in the TO's Licensee Specific Appendix.

Distance to Coast, Altitude and Corrosion Factor values are derived via calibration tables in the respective TO's Licensee Specific Appendices.

4.1.1.3. EXPECTED LIFE FACTOR

Starting with the Expected Average Life (L_A), the Duty and LSE factors are used to set an expected life (L_E) for each asset.

Equation 32

$$L_E = \frac{L_A}{F_{LSE} \times F_{DY}}$$

This expected life is then used to determine EoL_1.

The Expected Asset Life is the time (in years) in an asset's life when it would be expected to such deterioration that it is likely to exhibit functional failure. The determination of the L_A considers factors such as original specification and manufacturer data. This corresponds to an EoL Modifier of 5.5.

4.1.1.4. EOL1 CALCULATION

The initial EOL modifier is calculated as:

Equation 33

$$EoL_1 = \min\left((EoL_{New} \cdot \exp\{\beta_1 \cdot Age\}), EoL_{1,max}\right)$$

Where:

$EOL_{1,\,max}$ is 5.5

And $EoL_{1,i}$ is the Initial Indicator of asset I calculated as:

Equation 34

$$EoL_{1,i} = EoL_{New} \cdot \exp\{\beta_{1,i} \cdot Age_i\}$$

where:

$EoL_{1,i}$ =   Initial Indicator of asset i

EOL_{New} =   Indicator of a new asset (normally set to 0.5)

$\beta_{1,i}$ =   Initial Ageing Rate of asset i (Section 2.2.1)

4.1.2.   INTERMEDIATE END OF LIFE MODIFIER

The Transformer Intermediate End of Life Modifier is calculated per Sections 2.1.1.2. & 2.2.2. for Factors:

- Visual Condition
- Defect History
- Generic Reliability
- Oil Condition
- Operational restrictions

Additional Factors that can be included in the calculation of FV_1 are shown below:
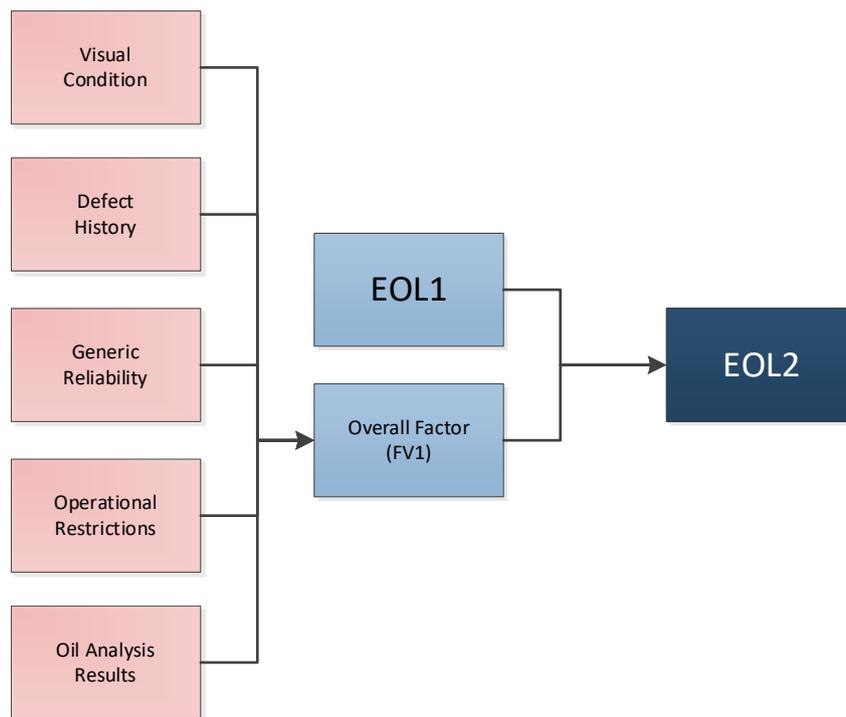
Figure 10 Transformer Intermediate EoL

The parameters used in the derivation of the overall factor value using the "Maximum and Multiple Increment" combination method, as set out Section 2.2.2.1, are provided in the licensee specific appendices.

Visual Condition

The observed condition of the transformer is evaluated through visual assessment by operational staff.

Several components of the transformer are assessed individually and assigned a condition. Condition is assessed on a 1-5 scale for SPT (1 = new or as new, 5 = intervention required) and a 1-4 scale for SSENT (1 = new or as new, 4 = intervention required). Each component's condition is weighted differently, based on the significance of the component, to create a factor and a minimum EoL.

Each TO's License Specific Appendix provides the calibration values associated with each score.

The condition factors are combined using the ' "Maximum and Multiple Increment" combination method to determine the Overall Condition Factor. The Overall Condition Minimum EoL is the maximum of the individual condition minimum EoLs.

Defects History

Defect history provides a useful way of identifying assets that are approaching the point at which the probability of failure is starting to increase. An asset that has experienced a high number of defects would be expected to have a higher End of Life Indicator than an otherwise similar asset which has not experienced any defects, even after the defects have been repaired.

Each of the recorded transformer defects from the past 5 years is assigned a severity score. The severity scores are summed, and the total score is used to derive the Defect History Factor and minimum EoL. Each TO's License Specific Appendix provides the calibration values associated with each score.

Generic Reliability

Reliability of specific groups or families of assets is determined using experience of assets in operation. A reliability rating (from 1-4, with 1 being Very Reliable and 4 being Very Unreliable) is assigned based on manufacturer and model. The reliability rating is then linked to a Generic Reliability Factor and a minimum EoL value via calibration tables as shown the respective TO's License Specific Appendices.

Operational Restrictions

When a significant issue is identified regarding a family of transformers, an Operator can issue a NEDER which notifies all other operators. This is called an Operational Restriction (OR). Each OR is assigned a severity, which then generates an Operational Restriction Factor and a minimum EoL via calibration tables as shown in in the respective TO's License Specific Appendices.

Oil Condition Factor:

Established techniques such as oil analysis provide an effective means of identifying and quantifying degradation of the insulation system (oil and paper) within transformers. Oil results can also be used to identify incipient faults. The oil condition factors can consider the latest oil condition tests, (moisture (O_M), acidity (O_A), breakdown strength(O_B) or tan delta(O_T)) each of which can be used to create a test score. Each of these scores can be given a multiplier which accounts for the significance of the result. The summation of these multiplied individual oil condition test scores, O_{TOTAL}, is then used to determine an overall oil condition factor, F_{OIL}.

Where the oil test is not considered to be valid it is excluded, and the next available set of results are used. Oil condition is not included if the latest sample is beyond the cut-off date.

Equation 35

$$O_{TOTAL} = sum\left(\left(O_M \times O_{M\_M}\right) + \left(O_B \times O_{B\_M}\right) + \left(O_T \times O_{T\_M}\right) + \left(O_A \times O_{A\_M}\right)\right)$$

Where:

O_M = Oil Moisture Score
O_{M_M} = Oil Moisture Multiplier
O_B = Oil Breakdown Score

O_{B_M} = Oil Breakdown Multiplier

O_T = Oil Tan delta score

O_{T_M} = Oil Tan delta Multiplier

O_A = Oil Acidity score

O_{A_M} = Oil Acidity Multiplier

The Oil Condition Factor is further expanded upon in the Transformer section of the Licensee Specific Appendices.

Overall Factor value FV1

The condition factors are combined using the "Maximum and Multiple Increment" combination method to determine the Overall Condition Factor. The Overall Condition Minimum EoL is the maximum of the individual condition minimum EoLs. The calibration values required to apply the method can be found in each TO respective Licensee Specific Appendix

4.1.2.1.   CALCULATION OF EOL MODIFIER (EOL$_2$)

To calculate an Intermediate End of Life modifier, the initial end of life modifier is simply multiplied by a conditional factor value.

Equation 36

$$EoL_2 = EoL_1 \times FV_1$$

4.1.3.   FINAL END OF LIFE MODIFIER
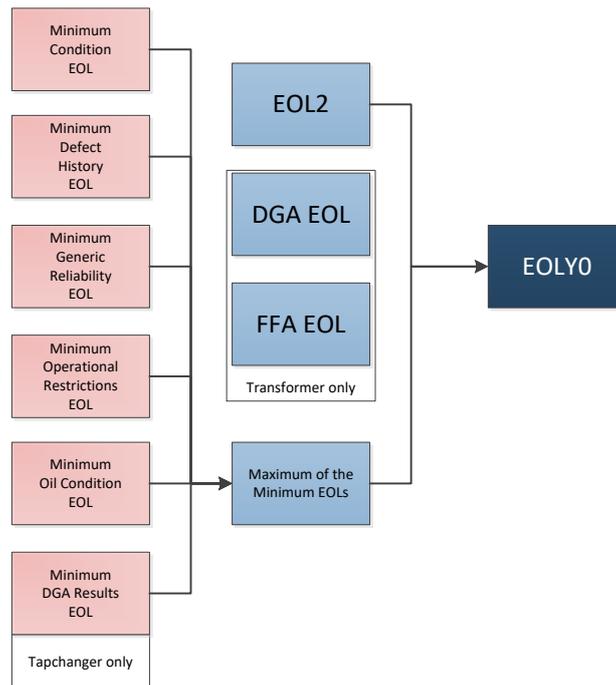
Figure 11 Main Tank Final EoL_{y0} Calculation Process

The following Modifiers are used to determine the Transformer End of Life Modifier ($TxEoL_{Y0}$):

- EoL_2
- EoL_{DGA}
- EoL_{FFA}
- Maximum of the Minimums

It can be calculated in one of two ways, based on the value of EoL_2:

If EoL_2 is the largest of the modifiers, then;

Equation 37

$$TxEoL_{y0} = Max\left(EoL_2 - \left[\left(\frac{EoL_2 - Max(EoL_{DGA}, EoL_{FFA})}{2}\right)\right], Maximum\ of\ the\ Minimums\right)$$

Otherwise,

Equation 38

$$TxEoL_{y0} = Max(EoL_{DGA}, EoL_{FFA}, Maximum\ of\ the\ Minimums)$$

4.1.3.1. DGA MODIFIER EOL_{DGA}

Internal Use

EoL_{DGA} is derived from the dissolved gas analysis (DGA) oil test results. This is a very well-established process that enables abnormal electrical or thermal activity to be detected by measurement of hydrogen and hydrocarbon gases that are breakdown products of the oil. The levels and combination of gases enable detection of developing faults and identification of 'life threatening' conditions.

The calculation of EoL_{DGA} can be split into two parts. In the Part 1 EoL_{DGA} is calculated for each oil sample held against an asset in the company's oil database. Each oil sample is analysed for levels of Hydrogen, Acetylene, Ethane, Ethylene, Methane, Oxygen and Nitrogen which provide indications of the internal condition of the transformer. Each gas result is then combined with weighted multipliers and then summed together to form a DGA Score. Finally, the DGA Score is compared with a calibration table to generate EoL_{DGA} for each sample.

In Part 2 a Principal Result is selected from the valid oil samples of each asset. The Principal Result is selected as the sample that provides the largest EoL_{DGA} within a calibrated time period of the latest sample (usually 90 days). The Principal Result is taken forward and modified in Part 2 by considering the rate of change of DGA values from each transformer's historical test results. The boundaries for assessment of DGA levels are taken from the Cigre Working Group 15.01 paper, "New guidelines for interpretation of dissolved gas analysis in oil-filled transformers". These boundaries can provide useful information relating to incipient faults within transformers or contamination of the main tank oil from the tapchanger.

Where the oil test is not considered to be valid it is excluded, and the next available set of results are used.

EoLDGA is capped at a maximum value of 10 and collared at a minimum value of 0.5. The step-by-step process is as follows:

Part 1

1. Convert each gas result (in ppm) to a Condition Score via a calibration table as per each TO's Specific License Appendix
2. Calculate the DGA Score by multiplying each gas Condition State by a multiplier and summing

Equation 39

$$DGA\ Score\ =\ \sum 50 \times Hydrogen\ Score + 30 \times Methane\ Score\ +\ 30 \times Ethylene\ Score$$
$$+\ 30 \times Ethane\ Score + 120 \times Acetylene\ Scores$$

3. Calculate EoL_{DGAi}

Equation 40

$$EoL_{DGAi} =\ min\left(\frac{DGA\ Score}{DGA\ Divider}, EoL_{DGA\ Max}\right)$$

Where:
EoL_{DGAMax} = Calibration value set in the LSA
DGA Divider = Calibration value set in the LSA

Part 2:
1. Calculate DGA % Change by the maximum DGA that has been recorded against the asset, then dividing by the average DGA recorded

42

Equation 41

$$DGA \ \% \ Change = \left(\frac{max(EoL_{DGAi})}{average(EoL_{DGA})} \right) \times 100$$

2. Convert DGA % Change to a Change Description via a calibration table
3. Generate a DGA History Factor from the Change Description via a calibration table as per each TO's Specific License Appendix

4. Calculate the final EoL$_{DGA}$ for each asset using the Principal Result

Equation 42

$$Principal \ Result = max(EoL_{DGAi}) \text{ in the calibrated time period before the last sample}$$

$$EoL_{DGA} = max(min(IF(PrincipalResult \\ > DGA \ History \ Threshold, Principle \ Result \\ \times DGA \ History \ Factor, Principle \ Result), 10), 0.5)$$

Where:
DGA History Threshold as set in the LSA

4.1.3.2. FFA MODIFIER EOL$_{FFA}$

EoL$_{FFA}$ is derived from the oil test results furfuraldehyde (FFA) value. Furfuraldehyde is one of a family of compounds (furans) produced when the cellulose (paper) within the transformer degrades. As the paper ages, the cellulose chains progressively break, reducing the mechanical strength.

The average length of the cellulose chains is defined by the degree of polymerisation (DP) which is a measure of the length of chains making up the paper fibres. In a new transformer, the DP value is approximately 1000. When this is reduced to approximately 250 the paper has very little remaining strength and is at risk of failure during operation.

Equation 43

$$EoL_{FFA} = Min(FFA_{Multiplier} FFA_{MAX}{}^{FFAPV}, EoL_{FFAMAX})$$

Where:

FFA Multiplier	=	TO Specific calibrated values included in Licensee Specific Appendices
FFA Power Value	=	TO Specific calibrated values included in Licensee Specific Appendices
Max FFA	=	FFA measurement for an asset

Where the oil test is not considered to be valid it is excluded and the next available set of results are used.

Internal Use

The Calibration tables used for the FFA Modifier can be found in the Transformer section of the Licensee, Specific Appendix.

4.2. TAPCHANGER (TC)

The variables involved in the EoL calculations for Tap changers are the same as for the main tank, except for EoL$_{FFA}$. As there are no windings within a tap changer, this variable does not exist. Similarly, the DGA results are not as material within a tap changer and, as such, are incorporated into the calculation of EoL$_2$

4.2.1. INITIAL END OF LIFE MODIFIER

The Tapchanger Initial End of Life Modifier is calculated per Section 2.1.2. Factors specific to Transformers are described below:

4.2.1.1. DUTY FACTOR

For each tapchanger, the duty factor is calculated from the following variables:

- Tapcount factor, T_F
- High Wear Rate Factor, H_F, where there is a history of high contact wear within the tapchanger

The combination of these variables determines an overall duty factor using Equation 44.

Equation 44

$$F_{DY} = max(T_F, H_F)$$

The tap count factor, T_F is based on the number of operations per year. This is calculated based on the age of the tap-changer and the date the operations count was recorded and the operation count. The annual number of tap operations is then moderated by a scaling factor that takes account of the ability of different types of tap changer and speed (e.g. oil in tank / fast) to withstand a different number of operations. The resulting moderated annualised count is converted into the duty factor via a calibration table as shown in respective TO's Licensee Specific Appendices.

The model also has a facility for a high wear rate exception report which can be used to identify tapchangers that are known to experience a high number of operations. The high wear rate factor is set in the TO's Licensee Specific Appendices.

4.2.1.2. LSE FACTOR

The Transformer Initial End of Life Modifier is calculated per Section 2.1.2.2 where the LSE Factor is calculated as:

Equation 45

$$LSE\ Factor = (((Location\ Factor - Minimum\ Location\ Factor) \times Situation\ Factor) + Minimum\ Location\ Factor) \times Environment\ Factor$$

The Licensee Specific Appendix further explores the calibration tables used in the LSE calculation.

4.2.1.3.   EOL1 CALCULATION

The initial EOL modifier is calculated as:

Equation 46

$$EoL_1 = \min\left((EoL_{New} \cdot \exp\{\beta_1 \cdot Age\}), EoL_{1,max}\right)$$

Where:

$EOL_{1,\,max}$ is 5.5

And $EoL_{1,i}$ is the Initial Indicator of asset I calculated as:

Equation 47

$$EoL_{1,i} = EoL_{New} \cdot \exp\{\beta_{1,i} \cdot Age_i\}$$

where:

$EoL_{1,i}$ =   Initial Indicator of asset i

EOL_{New} =   Indicator of a new asset (normally set to 0.5)

$\beta_{1,i}$ =   Initial Ageing Rate of asset i (Section 2.2.1)

4.2.2.   INTERMEDIATE END OF LIFE MODIFIER

The Tapchanger Intermediate End of Life Modifier is calculated per Section 2.2.2 for Factors:

- Visual Condition
- Defects
- Generic Reliability
- Oil Condition
- Operational restrictions
- DGA Results

Additional Factors that can be included in the calculation of FV_1 are shown below:
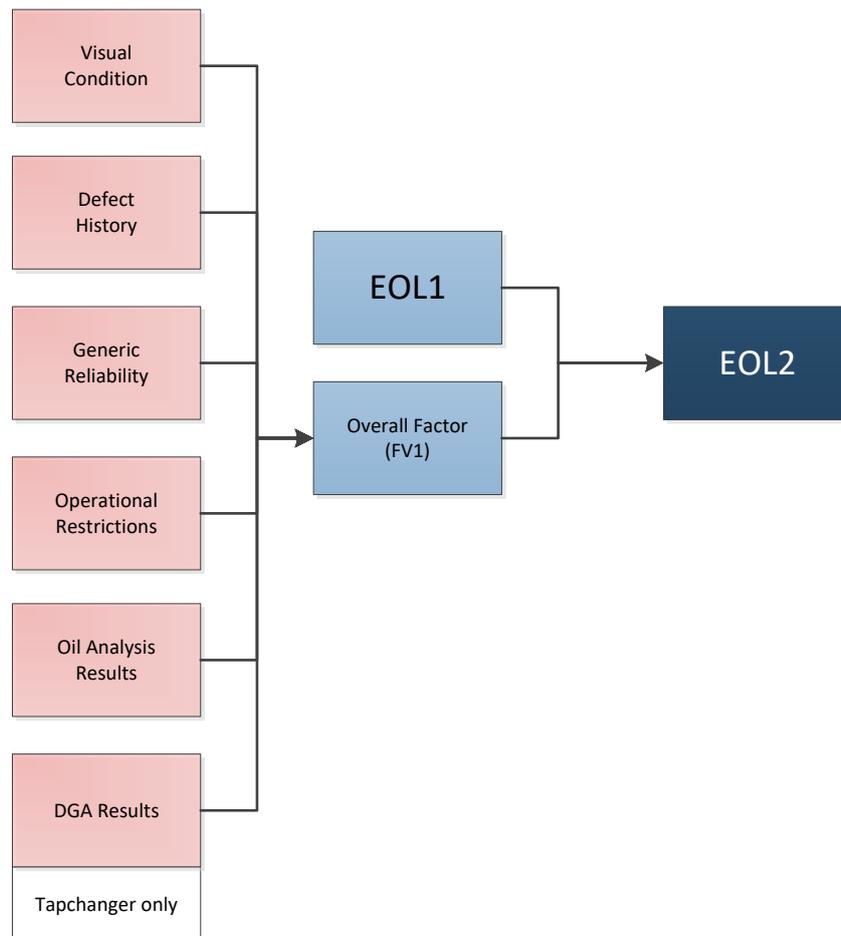
Figure 12 Tapchanger Intermediate EoL Modifier

The parameters used in the derivation of the overall factor value using the "Maximum and Multiple Increment" combination method, as set out Section 2.2.2.1, are provided in the licensee specific appendices.

Visual Condition

The observed condition of the tapchanger is evaluated through visual assessment by operational staff.

Several components of the transformer are assessed individually and assigned a condition. Condition is assessed on a 1-5 scale for SPT (1 = new or as new, 5 = intervention required) and a 1-4 scale for SSENT (1 = new or as new, 4 = intervention required). Each component's condition is weighted differently, based on the significance of the component, to create a factor and a minimum EoL.

Each TO's License Specific Appendix provides the calibration values associated with each score.

The condition factors are combined using the "Maximum and Multiple Increment" combination method to determine the Overall Condition Factor. The Overall Condition Minimum EoL is the maximum of the individual condition minimum EoLs.

Defects History

Defect history provides a useful way of identifying assets that are approaching the point at which the probability of failure is starting to increase. An asset that has experienced a high number of defects would be expected to have a higher End of Life Indicator than an otherwise similar asset which has not experienced any defects, even after the defects have been repaired.

Each of the recorded transformer tap changer defects from the past 5 years is assigned a severity score. The severity scores are summed, and the total score is used to derive the Defect History Factor and minimum EoL. Each TO's License Specific Appendix provides the calibration values associated with each score.

Generic Reliability

Reliability of specific groups or families of assets is determined using experience of assets in operation. A reliability rating (from 1-4, with 1 being Very Reliable and 4 being Very Unreliable) is assigned based on manufacturer and model. The reliability rating is then linked to a Generic Reliability Factor and a minimum EoL value via calibration tables as shown the respective TO's License Specific Appendices.

Oil Condition Factor:

Established techniques such as oil analysis provide an effective means of identifying and quantifying degradation of the insulation system (oil and paper) within transformers tapchangers. Oil results can also be used to identify incipient faults. The oil condition factors can consider the latest oil condition tests, (moisture (O_M), acidity (O_A), breakdown strength (O_B) or tan delta(O_T) each of which can be used to create a test score. Each of these scores can be given a multiplier which accounts for the significance of the result. The summation of these multiplied individual oil condition test scores, O_{TOTAL}, is then used to determine an overall oil condition factor, F_{OIL}.

Where the oil test is not considered to be valid it is excluded, and the next available set of results are used. Oil condition is not included if the latest sample is beyond the cut-off date.

The Oil Condition Factor is further expanded upon in the Transformer tapchanger section of the Licensee Specific Appendices.

Operational Restrictions

When a significant issue is identified regarding a family of transformer tapchangers, an Operator can issue a NEDER which notifies all other operators. This is called an Operational Restriction (OR). Each OR is assigned a severity, which then generates an Operational Restriction Factor and a minimum EoL via calibration tables as shown in in the respective TO's Licensee Specific Appendices.

DGA results

This factor is applied to tapchangers only and it is different from the DGA End of Life Indicator derived for transformers although it uses a similar methodology. The corresponding calibration values required for the calculation are available in each TO's Licensee Specific Appendix.

Overall Factor value FV1

The condition factors are combined using the "Maximum and Multiple Increment" combination method to determine the Overall Condition Factor. The Overall Condition Minimum EoL is the maximum of the individual condition minimum EoLs. The calibration values required to apply the method can be found in each TO respective Licensee Specific Appendix

4.2.2.1.   CALCULATION OF EOL MODIFIER (EOL$_2$)

To calculate an Intermediate End of Life modifier, the initial end of life modifier is simply multiplied by a conditional factor value.

Equation 48

$$EoL_2 = EoL_1 \times FV_1$$

4.2.3.   FINAL END OF LIFE MODIFIER

The following Modifiers are used to determine the Transformer End of Life Modifier (TxEoL$_{Y0}$):

- EoL$_2$
- Maximum of the Minimums

Equation 49

$$TcEoL_{y0} = Max(EoL_2, Maximum\ of\ the\ Minimums)$$

5. EOL CALCULATION FOR UNDERGROUND CABLES

Cables are assigned an Asset EoL Value (EoL) per their known condition and the service history of other similar cables.

Within this methodology, transmission cables are considered as number of discrete cable lengths (or 'component') which together form a distinct circuit.

For each component of a cable circuit asset, management information is fed into the model to produce an EoL Value. This EoL Value is then used to calculate a probability of failure, PoF for several defined failure modes.

There are two separate models within the main underground cable model reflecting the following types of construction;

- Pressurised (solid)
- Non-pressurised (fluid filled)

Each model uses a similar format, though certain condition points are 'construction' dependent and only used within that model as a factor.

5.1. INITIAL END OF LIFE MODIFIER

5.1.1. DUTY FACTOR

5.1.1.1. SSENT IMPLEMENTATION OF DUTY FACTOR

The duty factor is calculated based upon the maximum demand placed on the cable as a percentage of its rating. The following criteria are used to develop the duty factor;

In the case for non-pressurised (solid) cables

- Maximum Demand as a percentage (D_{max})
- A reactive earthing presence factor ($D_{reactive}$)

Equation 50

$$F_{DY} = D_{max} \cdot D_{reactive}$$

In the case for pressurised (fluid filled) cables

- Duty exception report ($D_{exception}$) is used instead of a reactive earthing presence factor

Equation 51

$F_{DY} = D_{max} \cdot D_{exception}$ As the effects of utilisation vary between cable types, separate duty factors will be established for each cable type. This classification will be based upon insulation type.

5.1.1.2. SPT IMPLEMENTATION OF DUTY FACTOR

Similarly, to SSENT, the duty factor is calculated based upon the maximum demand placed on the cable as a percentage of its rating. It uses the following criteria to develop a duty factor for all of its cables;

- Maximum load placed on the cable as a percentage of its rating (D_{max});
- Average load placed on the cable as a percentage of its rating (D_{ave}); and
- Operating voltage compared to design voltage (D_v).

Again, as the effects of utilisation vary between cable types, separate duty factors will be established for each cable type. This classification can also be based upon insulation type.

Equation 52

$$F_{DY} = D_{max} \cdot D_{ave} \cdot D_v$$

5.1.2. LSE FACTOR FOR UNDERGROUND CABLES

For underground Pressurised and Non-Pressurised Underground Cables, the installation factor can be based upon the following variables:

- As laid depth (F_{depth})
- Backfill Material (F_{back})
- Laying Configuration (F_{config})
- Duct Type (F_{duct})
- Ploughed installation factor (F_{plough})
- Mechanical Influence (F_{mech})
- Shallow Ducts ($F_{shallow}$)

The overall LSE factor is determined by TO specific equations, considering the cable type as required. The calculations for SSEN Transmission are given in Section 5.1.2.1 while the calculation for SPT is given in Section 5.1.2.2. In the model, section length is accounted for, this is done by sectioning the cable routes into similar lengths across the entirety of the cable. Each of these individual sections have their own unique identifier to which End of Life calculation incorporates allowing for an EoL value to be determined for all individual sections across a cable length.

5.1.2.1. SSEN TRANSMISSION LSE FACTOR FOR UNDERGROUND CABLES

For Non-Pressurised cable the LSE factor is calculated taking account of the duct depth and the nature of the cable laying as follows:

Equation 53 SSEN Transmission Cable LSE Factor for Non-Pressurised Cable

$$F_{LSE} = F_{shallow} \cdot F_{plough}$$

For Pressurised cable the LSE factor is set equal to the mechanical influence factor as follows:

Equation 54 SSEN Transmission Cable LSE Factor for Pressurised Cable

$$F_{LSE} = F_{mech}$$

5.1.2.2.   SPT LSE FACTOR FOR UNDERGROUND CABLES

The Installation Factor is derived by combining the Backfill Material Factor, Laying Configuration Factor, Duct Type Factor and As Laid Depth Factor using the following equation:

Equation 55 SPT Cable Installation Factor

$$F_{Inst} = F_{back} \cdot F_{config} \cdot F_{duct} \cdot F_{depth}$$

The Installation and Situation factors are then combined to derive the overall LSE Factor as follows:

Equation 56 SPT Cable LSE Factor

$$F_{LSE} = F_{Sit} \cdot F_{Inst}$$

5.1.3.   EXPECTED LIFE

Starting with the Expected Average Life (L_A), the Duty and LSE factors are used to set an expected life (L_E) for each asset.

Equation 57

$$L_E = \frac{L_A}{F_{LSE} \times F_{DY}}$$

This expected life is then used to determine EoL_1.

The Expected Asset Life is the time (in years) in an asset's life when it would be expected to such deterioration that it is likely to exhibit functional failure. The determination of the L_A considers factors such as original specification and manufacturer data. This corresponds to an EoL Modifier of 7.

5.1.4.   EOL1 CALCULATION

The initial EOL modifier is calculated as:

Equation 58

$$EoL_1 = \min\left((EoL_{New} \cdot \exp\{\beta_1 \cdot Age\}), EoL_{1,max}\right)$$

Where:

$EOL_{1, max}$ is 5.5

And $\text{EoL}_{1,i}$ is the Initial Indicator of asset I calculated as:

Equation 59

$$\text{EoL}_{1,i} = \text{EoL}_{\text{New}} \cdot \exp\{\beta_{1,i} \cdot \text{Age}_i\}$$

where:

$\text{EoL}_{1,i}$ = Initial Indicator of asset i

EOL_{New} = Indicator of a new asset (normally set to 0.5)

$\beta_{1,i}$ = Initial Ageing Rate of asset i (Section 2.2.1)

5.2. INTERMEDIATE END OF LIFE MODIFIER

The cable intermediate end of life modifier is calculated in accordance with Sections 2.1.1.2. & 2.2.2. for Factors:

- Visual Condition
- Defects
- Generic Reliability
- Test Results
- Operational restrictions

Additional Factors included in the calculation of FV_1 are:

- Fault History
- Leak History (for pressurised cables), as shown in Figure 13 below.

The factors used in the determination of the intermediate end of life modifier, EoL_2, are combined used in the "Maximum and Multiple Increment" combination method.
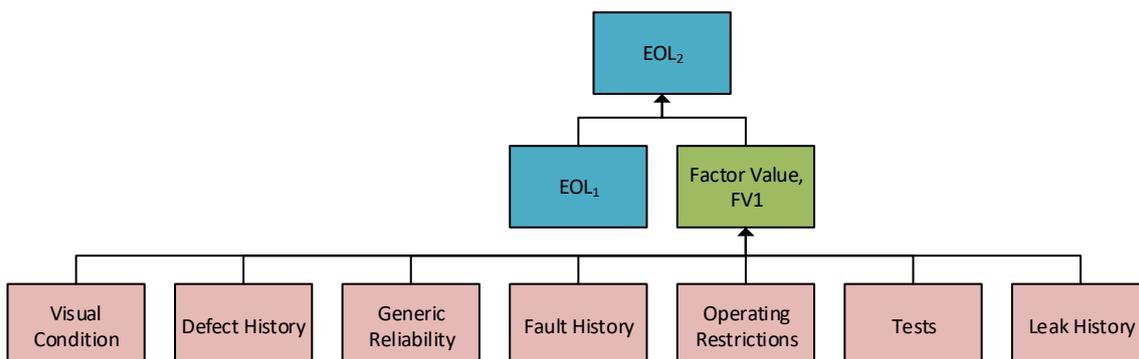
Figure 13 EoL₂ Calculation for Cables

Visual Condition

The observed condition of the cable system is evaluated through visual assessment by operational staff.

Several components of the cable which can be visually assessed individually and assigned a condition. Condition is assessed on a 1-5 scale (1 = new or as new, 5 = intervention required). Each component's condition is weighted differently, based on the significance of the component, to create a factor and a minimum EoL.

Each TO's License Specific Appendix provides the calibration values associated with each score.

The condition factors are combined using the "Maximum and Multiple Increment" combination method to determine the Overall Condition Factor. The Overall Condition Minimum EoL is the maximum of the individual condition minimum EoLs.

Defects History

Defect history provides a useful way of identifying assets that are approaching the point at which the probability of failure is starting to increase. An asset that has experienced a high number of defects would be expected to have a higher End of Life Indicator than an otherwise similar asset which has not experienced any defects, even after the defects have been repaired.

Each of the recorded cable defects from the past 5 years is assigned a severity score. The severity scores are summed, and the total score is used to derive the Defect History Factor and minimum EoL. Each TO's License Specific Appendix provides the calibration values associated with each score.

Generic Reliability

Reliability of specific groups or families of assets is determined by Licensee's using its experience of assets in operation. A reliability rating (from 1-4, with 1 being Very Reliable and 4 being Very Unreliable) is assigned on the following basis:

- oil cables - metallic screening type / armour type and period of manufacture;
- non-pressurised cables - armour type / insulation type and period of manufacture

The reliability rating is then linked to a Generic Reliability Factor and a minimum EoL value via calibration tables as shown the respective TO's License Specific Appendices.

Test Results

Testing may be undertaken on cables to provide a greater understanding of the operation of the asset. The tests that can be carried out vary according to the construction of the asset and its electrical configuration. Where testing is carried out the results are compared with reference values to allow a grading of the results. Calibration tables in the relevant Licensee Specific Appendices provide a mapping between the specific test results and the associated factor and minimum EoL values.

An Overall Combined Test Factor is calculated by combining the factors from each of the specific test types using the "Maximum and Multiple Increment" combination method. The Overall Combined Test Minimum EoL is the maximum of the individual test minimum EoLs.

Operational Restrictions

When a significant issue is identified regarding a family of cable, an Operator can issue a NEDER which notifies all other operators. This is called an Operational Restriction (OR). Each OR is assigned a severity, which then generates an Operational Restriction Factor and a minimum EoL via calibration tables as shown in in the respective TO's Licensee Specific Appendices.

Fault History

The number of condition related fault events experienced by a cable circuit can be used as an indicator of the potential for increased probability of asset failure in the future. Data on the previous fault experience is collated at a circuit level and converted to a Fault History factor using the mapping tables in each Licensee Specific Appendix. A minimum EoL value is determined in the same manner.

Leak History

The leak history information for a particular circuit is used to determine a Leak History Factor and an associated minimum EoL for each cable section based on the oil top-ups over a ten-year period.

A weighted total volume of top-ups is calculated by multiplying the volume of oil added each year by a weighting factor; this ensures that more recent top-ups have a greater effect on the value of the Leak History Factor and the minimum EoL. The weighting factor used for each of the 10 years can be found in the relevant Licensee Specific Appendix.

Each of the ten weighted values are summed and divided by the square root of the hydraulic section length as follows:

Equation 60

$$F_i = \frac{\sum_{j=1}^{10}(Vol_{cct,i,j} \cdot F_w)}{\sqrt{Length_i}}$$

Where:

F_i = Weighted volume of oil top-ups for cable section i

$Vol_{cct,i,j}$ = Volume of oil top-ups for cable section i in year j

$Length_i$ = Hydraulic length of cable section i

Tables are provided in the Licensee Specific Appendices which provide a mapping of the weighted volume of oil top ups with an Initial Leak History Factor (F_{ilh}) and an associated Minimum EoL value. The number of leaks recorded over the time period is also used to derive a Leaks Scaling Factor (F_{sf}) and associated Minimum EoL.

The final Leak History Factor, F_{LH}, is the product of the initial leak history factor and the number of leaks scaling factor as follows:

Equation 61

$$F_{LH} = F_{ilh} \cdot F_{sf}$$

The final Leak History Minimum EoL is the largest of the initial leak history minimum EoL and the number of leaks minimum EoL.

Overall Factor value FV1

The condition factors are combined using the "Maximum and Multiple Increment" combination method to determine the Overall Condition Factor. The Overall Condition Minimum EoL is the maximum of the individual

condition minimum EoLs. The calibration values required to apply the method can be found in each TO respective Licensee Specific Appendix

5.2.1.　　CALCULATION OF EOL MODIFIER (EOL$_2$)

To calculate an Intermediate End of Life modifier, the initial end of life modifier is simply multiplied by a conditional factor value.

Equation 62

$$EoL_2 = EoL_1 \times FV_1$$

5.3.　　FINAL END OF LIFE MODIFIER

The end-of-life modifier is calculated as shown below;

Equation 63

$$CableEoL_{y0} = Max(EoL_2, Maximum\ of\ the\ Minimums)$$
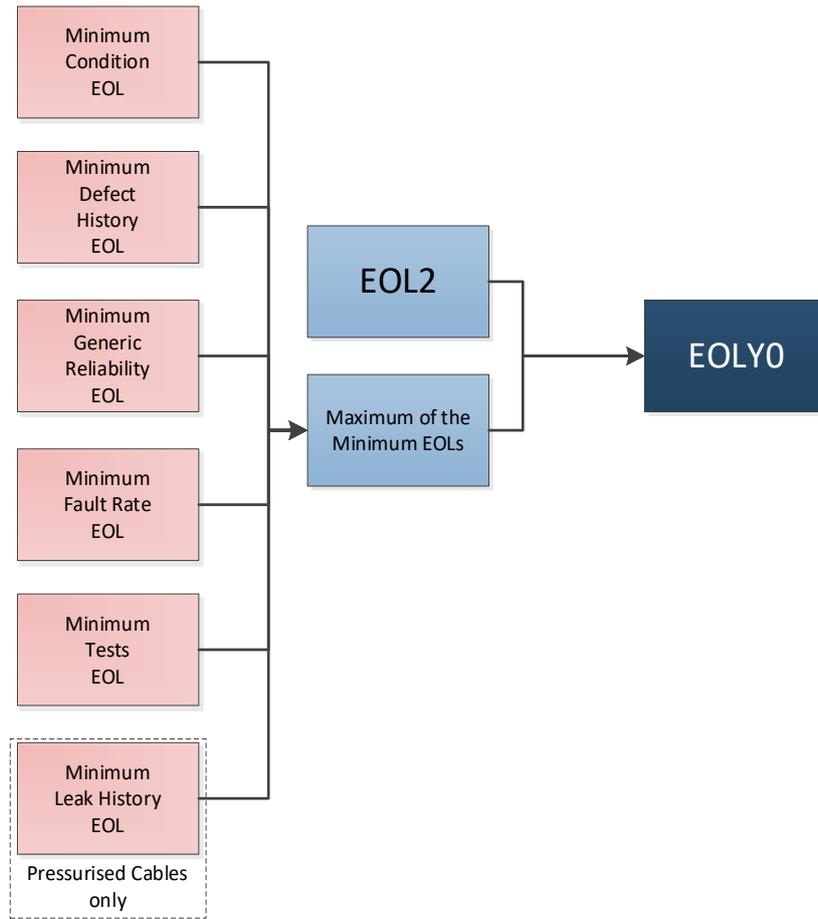
Figure 14 Final EoL Modifier

6. EOL CALCULATION FOR OVERHEAD LINES

OHL assets are assigned an asset EoL Value (EoL_{y0}) per their known condition, the known condition of associated components and the service history of other similar conductors, fittings and towers.

Within this methodology, three NARM Asset types are considered separately however they are, in combination, representative of an entire circuit.

- Conductors
- Fittings
- Towers
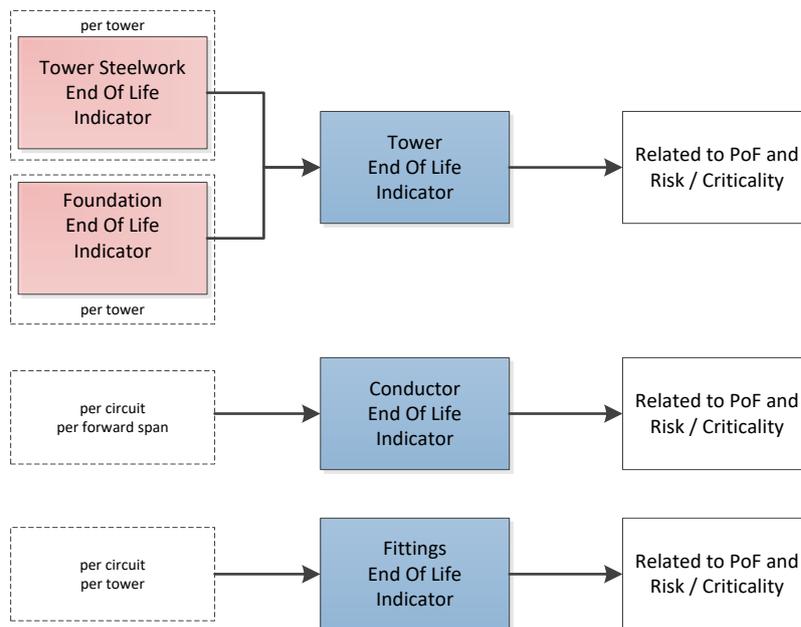
Figure 15 OHL System Overview

OHL System Overview

In addition to the 'per asset' EoL indices described above, the models will be able to include summary information by route for towers, and circuit name for spans.

In addition, the NARM Asset type of Steel Tower can be shared by multiple circuits.

6.1. CONDUCTORS

6.1.1. INITIAL END OF LIFE MODIFIER

The initial EoL indicator is based around the age of an asset in relation to the estimated average expected service life which could be reasonably anticipated. This calculation stage does not consider any condition, defect,

inspection or testing information, and simply provides an impression of the likely EoL of an asset given its age, where it is located and its approximate workload.

The asset's age is taken as the date at which the conductor was replaced; if no replacement date is available, it is assumed that the original conductor is still in place and the date of tower construction is used to determine the age of the conductor.

An average life is assigned to the conductor based on the conductor type and the cross-sectional area.

Duty is excluded as a factor within the conductor calculation.

6.1.1.1.   LOCATION, SITUATION AND ENVIRONMENT (LSE)

The Location and Environment factors are then combined to derive the overall LSE Factor, F_{LSE}, as follows:

$$F_{LSE} = F_{loc} \cdot F_{env}$$

The Location Factor is then derived by combining the three factors as follows:

$$F_{loc} = max(F_{dis}, F_{alt}, F_{cor})$$

Environment Factor

Environment also is a degrading factor for example if the conductor is in an area known to experience severe weather.

Further expansion of the calibration tables used to calculate the LSE can be found in the Licensee Specific Appendices.

6.1.1.2.   IMPLEMENTATION OF LSE FACTOR

The overall LSE factor is derived using the following equation:

Equation 64

$$LSE\ Factor = (((Location\ Factor - Minimum\ Location\ Factor) \times Situation\ Factor) \\ + Minimum\ Location\ Factor) \times Environment\ Factor$$

6.1.1.3.   EXPECTED LIFE

Starting with the Expected Average Life (L$_A$), the Duty and LSE factors are used to set an expected life (L$_E$) for each asset.

$$L_E = L_A \times F_{LSE}$$

This expected life is then used to determine EoL$_1$.

The Expected Asset Life is the time (in years) in an asset's life at which point is expected to have deteriorated to such an extent it is likely to exhibit functional failure. The determination of the L$_A$ considers factors such as original specification and manufacturer data. This corresponds to an EoL Modifier of 5.5.

6.1.1.4.   INITIAL EOL MODIFIER

The initial EOL modifier is calculated as:

Equation 66

$$EoL_1 = \min\left((EoL_{New} \cdot \exp\{\beta_1 \cdot Age\}), EoL_{1,max}\right)$$

Where:

EOL$_{1, max}$ is 5.5

And EoL$_{1,i}$ is the Initial Indicator of asset I calculated as:

Equation 67

$$EoL_{1,i} = EoL_{New} \cdot \exp\{\beta_{1,i} \cdot Age_i\}$$

where:

$EoL_{1,i}$ =   Initial Indicator of asset i

EOL_{New} =   Indicator of a new asset (normally set to 0.5)

$\beta_{1,i}$ =   Initial Ageing Rate of asset i (Section 2.2.1)

6.1.2.   INTERMEDIATE END OF LIFE MODIFIER

The conductor intermediate end of life modifier is calculated in accordance with Sections 2.1.1.2 & 2.2.2. for Factors:

- Visual Condition
- Defects
- Generic Reliability
- Test Results
- Operational restrictions

Additional Factors that can be included in the calculation of FV$_1$ are:

- Cormon Testing

- Conductor Hot Joints
- Flashover Marks, as shown in Figure 16 below;
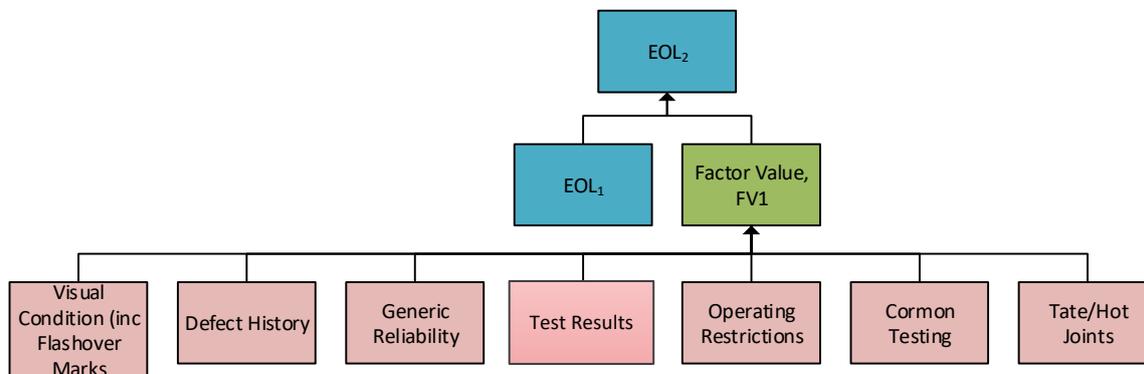
Figure 16 SSENT's Calculation for EoL_2

The parameters used in the derivation of the overall factor value using the "Maximum and Multiple Increment" combination method, as set out Section 2.2.2.1, are provided in the licensee specific appendices.

Visual Condition

The observed condition of conductor is evaluated through visual assessment by operational staff and drone imaging.

Limited information points are assessed individually and assigned a condition. Condition is assessed on a 1-5 scale for SPT (1 = new or as new, 5 = intervention required) and a 1-4 scale for SSENT (1 = new or as new, 4 = intervention required). Each component's condition is weighted differently, based on the significance of the component, to create a factor and a minimum EoL.

Each TO's License Specific Appendix provides the calibration values associated with each score.

The condition factors are combined using the "Maximum and Multiple Increment" combination method to determine the Overall Condition Factor. The Overall Condition Minimum EoL is the maximum of the individual condition minimum EoLs.

Defects History

Defect history provides a useful way of identifying assets that are approaching the point at which the probability of failure is starting to increase. An asset that has experienced a high number of defects would be expected to have a higher End of Life Indicator than an otherwise similar asset which has not experienced any defects, even after the defects have been repaired.

Each of the recorded conductor defects from the past 5 years is assigned a severity score. The severity scores are summed, and the total score is used to derive the Defect History Factor and minimum EoL. Each TO's License Specific Appendix provides the calibration values associated with each score.

Generic Reliability

Reliability of specific groups or families of assets is determined using experience of assets in operation. A reliability rating (from 1-4, with 1 being Very Reliable and 4 being Very Unreliable) is assigned on the basis of

manufacturer and model. The reliability rating is then linked to a Generic Reliability Factor and a minimum EoL value via calibration tables as shown the respective TO's License Specific Appendices.

Test Results

The methodology allows for several different ad hoc tests to be considered within the model. The calibration values required to create a test factor and associated minimum EOL are shown in the respective TO's License Specific Appendices.

Operational Restrictions

When a significant issue is identified regarding a family of conductor, an Operator can issue a NEDER which notifies all other operators. This is called an Operational Restriction (OR). Each OR is assigned a severity, which then generates an Operational Restriction Factor and a minimum EoL via calibration tables as shown in in the respective TO's License Specific Appendices.

Conductor Sampling/Cormon Testing

Conductor sampling determines the extent of corrosion a sample of the overhead conductor, which is considered to provide a representative indication of the EoL of the circuit. The results can be used to derive an EoL Modifier independently of any other information on condition or age.

The test results are used to derive a Conductor Sampling EoL Modifier via a calibration table of the form shown below.

Cormon testing measures the extent of corrosion on ACSR conductors, and can be used to derive a EoL indicator independently of any other information on condition or age.

Both tests, conductor sampling or cormon, are conducted on a span or number of spans and then applied to the whole circuit.

Conductor Hot Joints – SSENT Only

Infrared detection is used to check the thermal radiation given off by a conductor during operation. If a hot joint is detected (with a thermal value greater than a calibrated normal result) then it is assigned a factor value, Expanded further in Section 5.1.1.4 in the Licensee Specific Appendix. Once the factor is assigned a Maximum Multiple increment function is used (with tate joints condition factor) to determine and overall factor value.

Flash Over Marks – SSENT Only

The voltage problems that cause flash over rarely produce heat and are often undetected with typical infrared inspection. Therefore, if residual marks left over from flash over are detected then we can assume those fittings are incurring voltage problems which are causing visible damage to the system. A Boolean statement is used to determine if the flash over score is added to the overall score for determining fitting end of life which is then converted into a factor using a calibration table.

Overall Factor value FV1

The condition factors are combined using the "Maximum and Multiple Increment" combination method to determine the Overall Condition Factor. The Overall Condition Minimum EoL is the maximum of the individual condition minimum EoLs. The calibration values required to apply the method can be found in each TO respective Licensee Specific Appendix

6.1.2.1. CALCULATION OF EOL MODIFIER (EOL$_2$)

To calculate an Intermediate End of Life modifier, the initial end of life modifier is simply multiplied by a conditional factor value.

Equation 68

$$EoL_2 = EoL_1 \times FV_1$$

6.1.3. FINAL END OF LIFE MODIFIER

Test results provided by the Cormon testing or conductor sampling are the most robust indicator of end of life and, as such, if these results are present, the Test Factor is taken as a proxy for end of life. If these results are not present, EoL$_2$ is taken as the final EoL modifier.
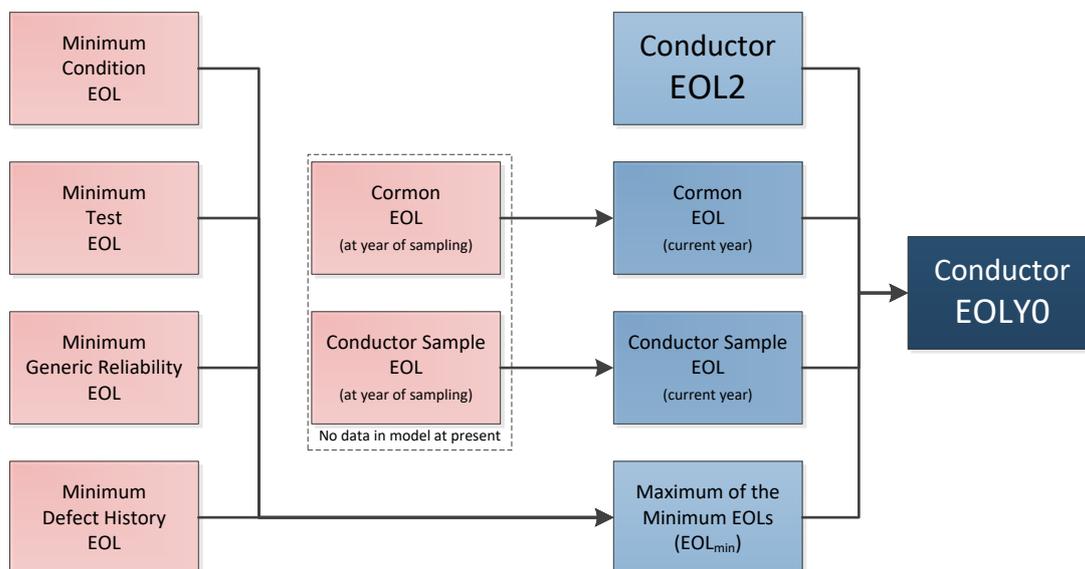
Figure 17 Derivation of the Conductor EoL$_{Y0}$

The Current End of Life Indicator is determined as follows:

(1) The Cormon EOL and Conductor Sample EoL are aged to the current year.

(2) If there is a Cormon EoL, EoL_{Corman}, available, then:

$EoLY0 = EoL_{Corman}$ where $EoL_{Corman} \leq EoL_{min}$

or

Equation 69

$EoLY0 = EoL_{min}$ where $EoL_{Corman} > EoL_{min}$

(3) If there is a Conductor Sample EoL, EoL_{sample}, available, then:

Internal Use

$$EoLY0 = EoL_{sample} \text{ where } EoL_{sample} \leq EoL_{min}$$

or

$$EoLY0 = EoL_{min} \text{ where } EoL_{sample} > EoL_{min}$$

(4)   If there is no Cormon Sample EOL or Conductor Sample EOL available, then:

$$EoLY0 = EoL2 \text{ where } EoL2 \leq EoL_{min}$$

or

$$EoLY0 = EoL_{min} \text{ where } EoL2 > EoL_{min}$$

6.2.   FITTINGS

To attach, insulate and join conductor spans various fittings and insulators are used. Over the course of the lifetime of these assets an EoL indicator needs to be calculated (on a per circuit and a per tower basis) as summarised in Figure 18 Initial End of Life Modifier for Fittings.

6.2.1.   INITIAL END OF LIFE MODIFIER – (EOL_C)

The initial EoL indicator is based around the age of an asset in relation to the estimated average expected service life which could be reasonably anticipated. This calculation stage does not consider any condition, defect, inspection or testing information, and simply provides an impression of the likely EoL of an asset given its age, where it is located and its approximate workload.

The initial End of life modifier is denoted by EoL_C instead of EoL_1. This is due to the way the Final end of life value is calculated. In previous equations, Initial end of life modifier (EoL_1) is *converted* into the Intermediate end of life modifier (EoL_2) by multiplication of a factor value. It should be noted that in this instance and the following instances in steel work and foundations (Section 6.3) calculating in this way is not comparable.

The initial End of Life value (EoL_C) is instead *compared* with the condition factors that would ordinarily constitute the Intermediate end of life modifier (for this case produced by EoL_A and EoL_B).

Comparing the values of EoL_A and EoL_B with EoL_C and taking the maximum value of these creates the Final End of life value as per 6.2.3 and is thus why they are denoted differently.
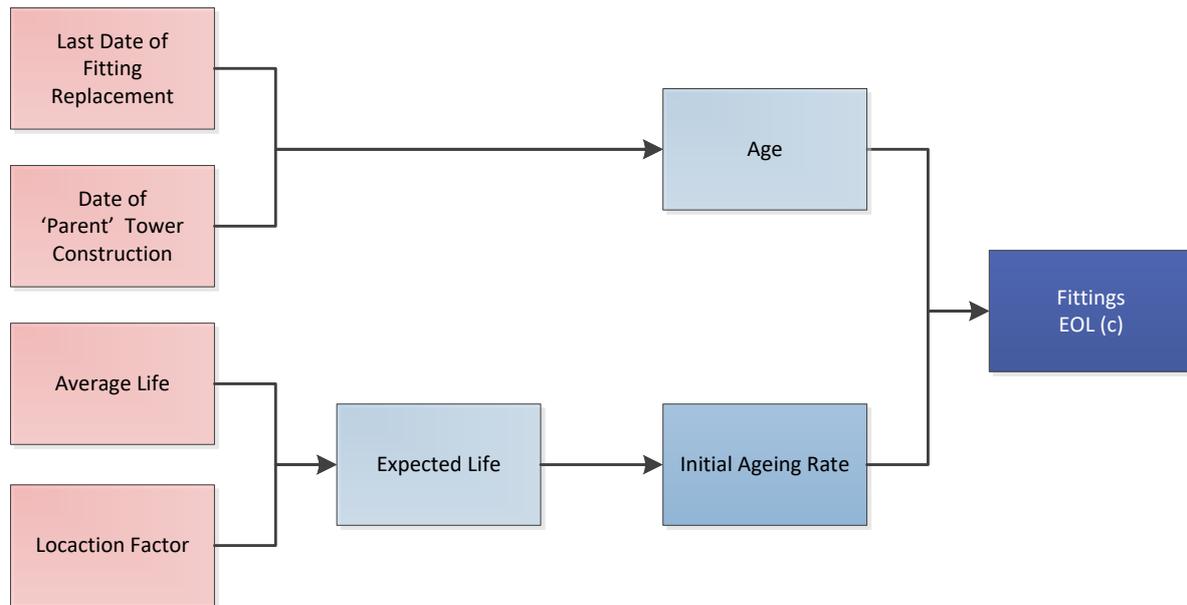
Figure 18 Initial End of Life Modifier for Fittings

The asset's age is taken as the date at which the fittings were replaced; if no replacement date is available, it is assumed that the original fittings are still in place and the date of tower construction is used to determine the age of the fittings.

An average life is assigned to the fittings based on the type of insulators (i.e. glass, polymeric or porcelain), whether they are tension/suspension fittings and the operating voltage.

6.2.1.1. DUTY FACTOR

For Steel Tower fittings, SSENT includes a duty factor in its calculation, high damper replacement can indicate too much vibration is being introduced into the system and therefore negatively affects the life expectancy of the tower.

Therefore, there is a calibration table used that modifies the value used calculate the Initial End of life modifier

Equation 72

$$Overall\ Duty\ Factor\ =\ High\ Damper\ Replacement\ Rate$$

It is to be noted that SPT do not include a duty factor in their calculation of the initial end of life modifier.

6.2.1.2. LOCATION, SITUATION AND ENVIRONMENT (LSE)

The Location and Environment factors are then combined to derive the overall LSE Factor, F_{LSE}, as follows:

Internal Use

$$F_{LSE} = F_{loc} \cdot F_{env}$$

The Location Factor is then derived by combining the three factors as follows:

$$F_{loc} = max(F_{dis}, F_{alt}, F_{cor})$$

Environment Factor

Environment also is a degrading factor for example if the conductor is in an area known to experience severe weather.

Further expansion of the calibration tables used to calculate the LSE can be found in the Licensee Specific Appendices.

6.2.1.3. EXPECTED LIFE

Starting with the Expected Average Life (L_A), the Duty and LSE factors are used to set an expected life (L_E) for each asset.

Equation 73

$$L_E = \frac{L_A}{F_{LSE} \times F_{DY}}$$

This expected life is then used to determine EoL_c.

The Expected Asset Life is the time (in years) in an asset's life when it would be expected to such deterioration that it is likely to exhibit functional failure. The determination of the L_A considers factors such as original specification and manufacturer data. This corresponds to an EoL Modifier of 5.5.

6.2.1.4. EOL(C) MODIFIER CALCULATION

The initial EOL_C modifier is calculated as:

Equation 74

$$EoL_C = min\left((EoL_{New} \cdot exp\{\beta_C \cdot Age\}), EoL_{C,max}\right)$$

Where:

$EOL_{C, max}$ is 5.5

And $EoL_{1,i}$ is the Initial Indicator of asset I calculated as:

$$EoL_{C,i} = EoL_{New} \cdot \exp\{\beta_{C,i} \cdot Age_i\}$$

where:

$EoL_{C,i}$ =   Initial Indicator of asset i

EOL_{New} =   Indicator of a new asset (normally set to 0.5)

$\beta_{C,i}$ =   Initial Ageing Rate of asset i (Section 2.2.1)

6.2.2.   INTERMEDIATE END OF LIFE MODIFIERS

6.2.2.1.   CONDITION

Where reliable and robust information provides definitive information on asset condition, the information is used to directly derive a condition based EoL indicator. This is depicted in the schematic diagram shown in **Error! Reference source not found.** below. Several individual condition points are assessed or rated using a pre-defined scale (typically 1 to 4 or 1 to 5). Each condition rating is then assigned a condition score via a calibration table. Each condition point has its own specific calibration table for defining the condition score.

Internal Use
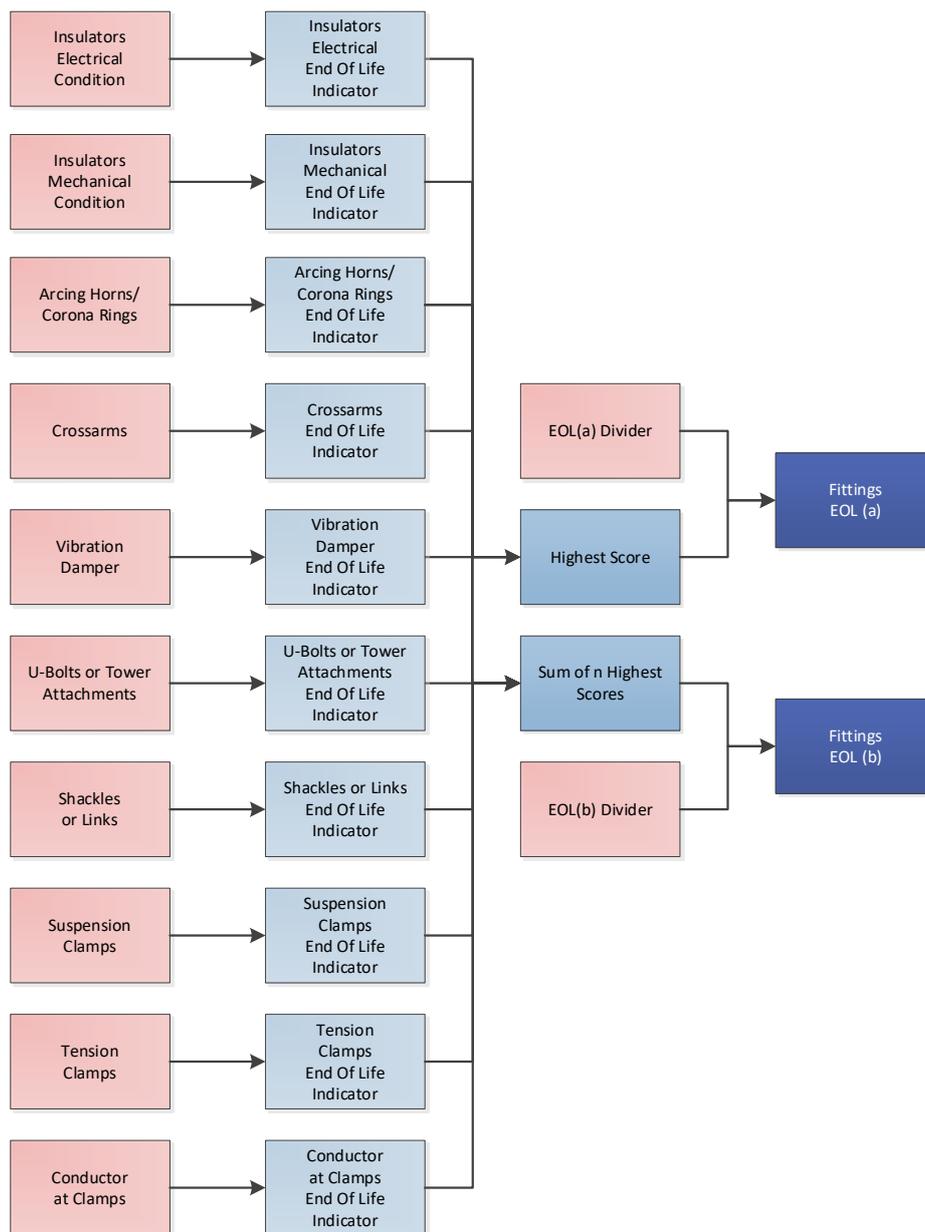
Figure 19   Derivation of EoL(a) and EoL(b)

Visual Condition

The observed condition of the fittings are evaluated through visual assessment by operational staff.

Several components of the fittings are assessed individually and assigned a condition. Condition is assessed on a 1-5 scale for SPT (1 = new or as new, 5 = intervention required) and a 1-4 scale for SSENT (1 = new or as new, 4 = intervention required). Each component's condition is weighted differently, based on the significance of the component, to create a factor and a minimum EoL.

Each TO's License Specific Appendix provides the calibration values associated with each score.

The condition factors are combined using the ' "Maximum and Multiple Increment" combination method to determine the Overall Condition Factor. The Overall Condition Minimum EoL is the maximum of the individual condition minimum EoLs.

EoL_a and EoL_b are two possible values for the condition based EoL indicator derived by combining the individual condition scores in two different ways. This ensures that a 'worst case' EoL indicator is derived regardless of whether the fittings have only one element in very poor condition or several elements in moderately poor condition.

Equation 76

$$EoL_A = Max(Highest\ Score \div EoL_A Dividing\ Number, MinEoL)$$

Where:
Highest Score = the highest condition score recorded
EoL_A Dividing Number = Set in the LSA calibration tables
MinEoL = the minimum HI score applicable for the condition scores

Equation 77

$$EoL_B = Max(Sum\ of\ Worst\ Score\ Points \div EoL_B\ Dividing\ Number, MinEoL)$$

Where:
Sum of Worst Score Points = Sum of the worst scores recorded against the asset
EoL_B Dividing Number = Set in the LSA calibration tables
MinEoL = the minimum HI score applicable for the condition scores

6.2.3. FINAL END OF LIFE MODIFIER

The end of life modifier is calculated as shown below:
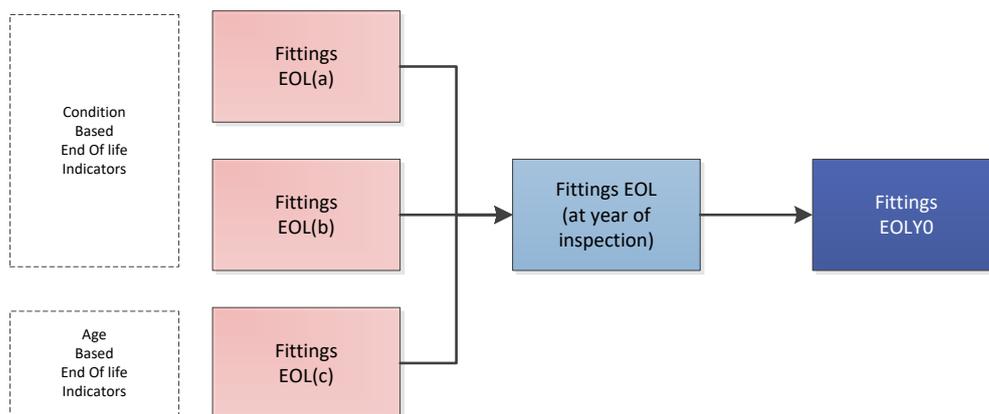
Figure 20 Derivation of Fittings Current End of Life Indicator

Equation 78

$$EoL_{y0} = IF\ (EoL_A, EoL_B)\ are\ NULL\ , EoL_C, MAX\ (EoL_A, EoL_B)\ \times\ \exp\{\beta_{1,i} \cdot Age_i\}$$

Firstly, an interim End of Life Indicator for the fittings (i.e. in the year of inspection) is derived as follows:

- if there is no condition data available, i.e. there is no value for either EoL(a) or EoL(b), then the age based End of Life Indicator, EoL(C) is used, capped at a maximum of 5.5; or

- if condition data is available, i.e. values have been derived for EoL(a) and EoL(b), then the maximum of EoL(a) and EoL(b) is taken

The Fittings Current End of Life Indicator is then derived by ageing the interim End of Life Indicator using the Age constant:

$\beta_{1,i}$ =   Initial Ageing Rate of asset i (Section 2.2.1)

6.3.   TOWERS

The steel tower EoL Value is formed from a combination of a steelwork EoL and a tower foundation EoL Values, as shown in Figure 21 below.

Please note there is a difference in calculation for SPT and SSENT.
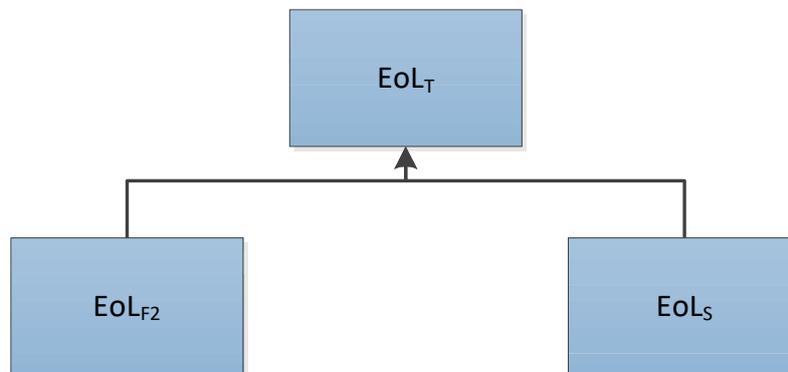
Figure 21 Steel Tower EoL Value

6.3.1.   STEELWORK

6.3.1.1.   INITIAL END OF LIFE MODIFIER

An 'age based' EoL indicator, EoL_C, is derived from the asset age, last painting date and the expected service life of the tower as shown in Figure 22 below. This is only used

i.   if no inspection data is available to derive EoL_A and EoL_B, or

ii.   to provide boundaries for the EoL derived from inspection data.
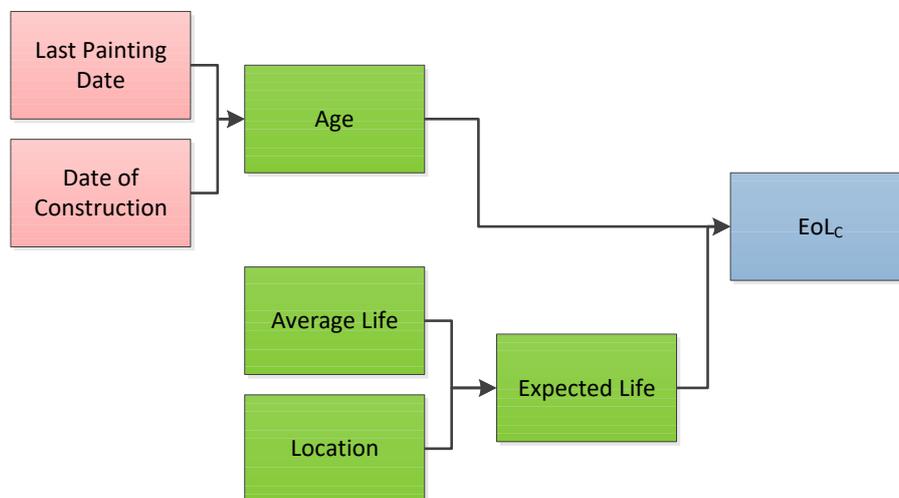
Figure 22 Steelwork EoL indicator EoL(c)

The asset's age is taken from the date of tower construction and where it exists, the date at which the tower was last painted. If a tower has been painted then the expected life of the tower will be set via calibration to an expected life associated with the paint system, typically in the region of 15 years. If the tower has not been painted the year of construction is used against an expected life which is associated with the original tower steelwork galvanising, a calibration value typically set at around 30 years.

Duty is excluded as a factor within the tower calculation.

6.3.1.2.   LSE FACTOR

The Location and Environment factors are then combined to derive the overall LSE Factor, F_{LSE}, as follows:

$$F_{LSE} = F_{loc} \cdot F_{env}$$

The Location Factor is then derived by combining the three factors as follows:

$$F_{loc} = max(F_{dis}, F_{alt}, F_{cor})$$

Environment Factor

Environment also is a degrading factor for example if the conductor is in an area known to experience severe weather.

Further expansion of the calibration tables used to calculate the LSE can be found in the Licensee Specific Appendices.

6.3.1.3.   EXPECTED LIFE FACTOR

Starting with the Expected Average Life (L$_A$), the Duty and LSE factors are used to set an expected life (L$_E$) for each asset.

Equation 79

$$L_E = \frac{L_A}{F_{LSE} \times F_{DY}}$$

This expected life is then used to determine EoL$_1$.

The Expected Asset Life is the time (in years) in an asset's life when it would be expected to such deterioration that it is likely to exhibit functional failure. The determination of the L$_A$ considers factors such as original specification and manufacturer data. This corresponds to an EoL Modifier of 5.5.

6.3.1.4. EOL$_C$ CALCULATION

The initial EOL modifier is calculated as:

Equation 80

$$EoL_C = \min\left((EoL_{New} \cdot \exp\{\beta_C \cdot Age\}), EoL_{C,max}\right)$$

Where:

EOL$_{C,\ max}$ is 5.5

And $EoL_{C,i}$ is the Initial Indicator of asset I calculated as:

Equation 81

$$EoL_{C,i} = EoL_{New} \cdot \exp\{\beta_{C,i} \cdot Age_i\}$$

where:

$EoL_{C,i}$ =   Initial Indicator of asset i

EOL_{New} =   Indicator of a new asset (normally set to 0.5)

$\beta_{C,i}$ =   Initial Ageing Rate of asset i (Section 2.2.1)

6.3.1.5. INTERMEDIATE END OF LIFE MODIFIERS

The first stage of the steelwork EoL indicator is derived using the observed condition information collated from surveys and inspections, as shown in **Error! Reference source not found.** below.
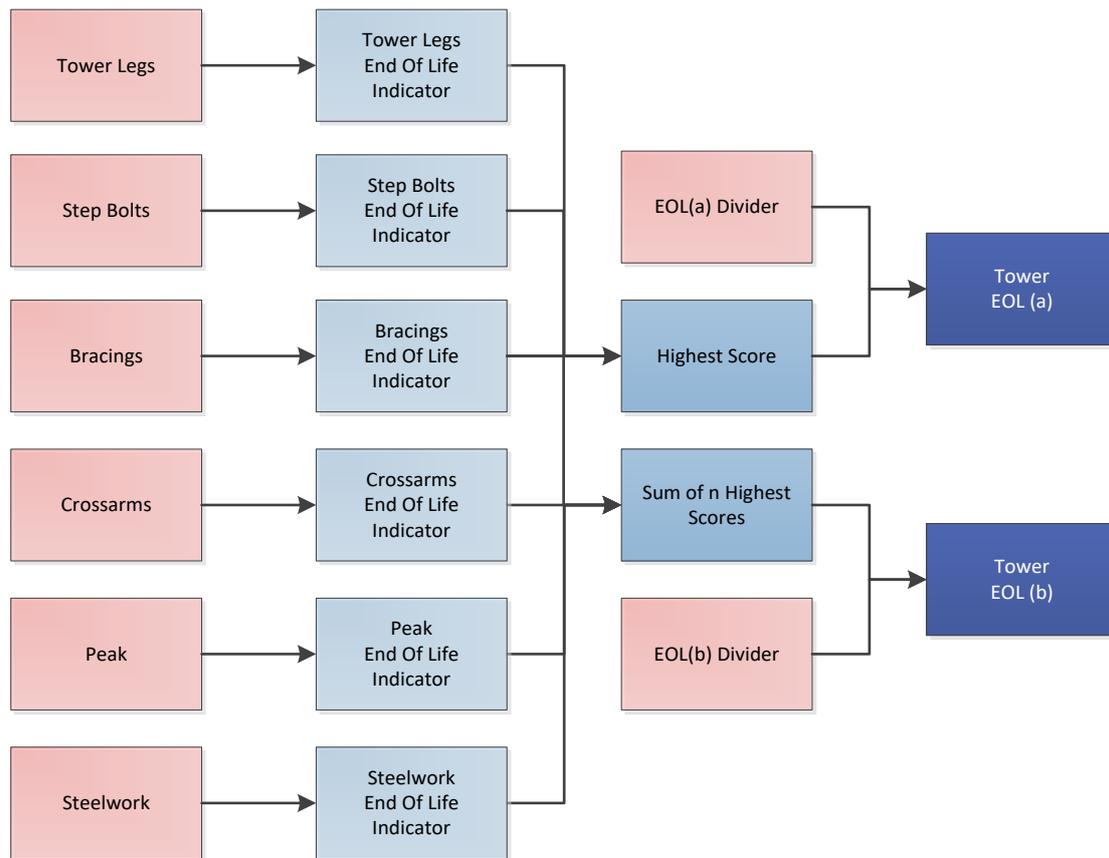
Figure 23 Derivation of EoL(a) and EoL(b)

Visual Condition

The observed condition of the fittings are evaluated through visual assessment by operational staff.

Several components of the fittings are assessed individually and assigned a condition. Condition is assessed on a 1-5 scale for SPT (1 = new or as new, 5 = intervention required) and a 1-4 scale for SSENT (1 = new or as new, 4 = intervention required). Each component's condition is weighted differently, based on the significance of the component, to create a factor and a minimum EoL.

Each TO's License Specific Appendix provides the calibration values associated with each score.

The condition factors are combined using the "Maximum and Multiple Increment" combination method to determine the Overall Condition Factor. The Overall Condition Minimum EoL is the maximum of the individual condition minimum EoLs.

EoL_a and EoL_b are two possible values for the condition based EoL indicator derived by combining the individual condition scores in two different ways. This ensures that a 'worst case' EoL indicator is derived regardless of whether the fittings have only one element in very poor condition or several elements in moderately poor condition.

Equation 82

$$HighestScore = MAX(TowerLegScore, StepBoltScore, BracingsScore, CrossarmsScore, PeakScore, SteelworkScore)$$

Where:

Scores are determined in the LSA

Equation 83

$$EolA = MAX(HighestScore \ / \ EoLa \ Dividing \ Number \ , MinEoL)$$

Where:

EoL_A Dividing Number = Calibration table in LSA

MinEoL = Min EoL allowed for score values

Equation 84

$$EolB = MAX(Sum \ of \ Worst \ Scores \ Points \ / \ EoLb \ Dividing \ Number, MinEoL)$$

Where:

Sum of Worst Scores Points = Combined scores of the highest scoring assessment points, the number of these are in the LSA calibration tables.

EoL_B Dividing Number = Calibration table in LSA

6.3.1.6.   FINAL END OF LIFE MODIFIER

The final tower steelwork EoL indicator, EoL_S, which represents the present day overall condition of the tower steelwork is determined from EoL_A, EoL_B and EoL_C as depicted below.
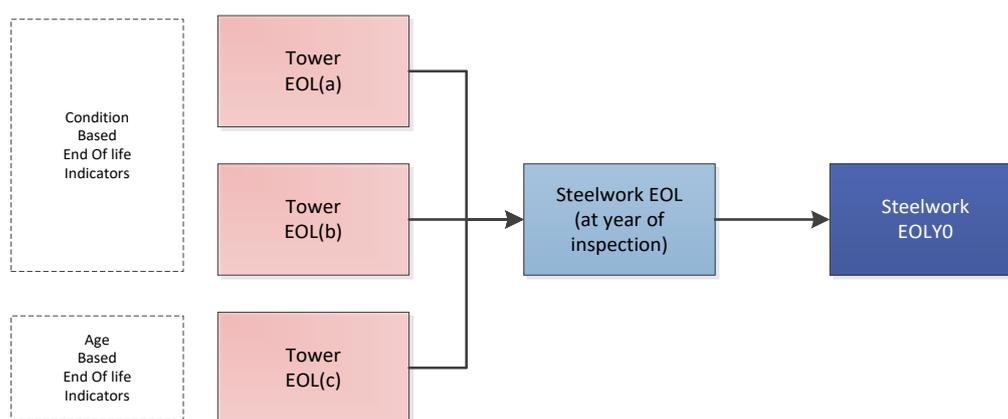
Figure 24 Derivation of Steelwork End of Life Indicator EoL(c)

Where detailed condition assessment information is not available, the model will not be able to calculate EoL_A or EoL_B, and therefore EoL_S will equal EoL_C.

Where detailed condition information is available the final tower steelwork EoL indicator, EoL_S, will be the maximum of EoL_A and EoL_B. If the condition assessment identifies that the tower steelwork is in as-new condition, then the model will use EoL_C to modify the EoL indicator depending upon the age of the tower up to a calibratable limits which is typically set at an EoL of around 1.5.

Internal Use

Equation 85

$$EoL_{y0} = IF\ (EoL_A, EoL_B\ )\ are\ NULL\ , EoL_C, IF(AND(EoL_A, EoL_B = 0.5, 2, MAX\ (EoL_A, EoL_B) \times \exp\{\beta_{1,i} \cdot Age_i\}$$

Firstly, an interim End of Life Indicator for the tower steelwork (i.e. in the year of inspection) is derived as follows:

● if there is no condition data available, i.e. there is no value for either EoL(a) or EoL(b), then the age-based End of Life Indicator, EoL(c)c is used, capped at a maximum of 5.5; or

● if condition data is available, i.e. values have been derived for EoL(a) and EoL(b), then the maximum of EoL(a) and EoL(b) is taken, unless;

● if both EoL(a) and EoL(b) are 0.5, indicating that all condition points have been assigned a rating of 1 (i.e. the steelwork is considered to be in very good condition) the End of Life Indicator is limited to a maximum value of 2.

The Steelwork Current End of Life Indicator is then derived by ageing the interim End of Life Indicator.

SSEN Transmission have an additional step where the Steelwork is then weighted.

Equation 86

Steelwork Weighted – SSENT Only

$$EoLsWeighted = EoL_{y0}\ x\ EoLY0_{weighting}$$

Where:
EoLY0$_{weighting}$ = calibrated look up value in the LSA.

6.3.2.   FOUNDATIONS

The Implementation calculates an EoL indicator for each set of tower foundations for each tower position. The model uses information relating to the type of foundation, the environment in which the foundation is situated, along with more specific foundation test results and inspection information. SPT and SSENT follow different calculation methodologies for foundations, for clarity there is a section for each company specific methodology.

6.3.2.1.   FOUNDATIONS-SSENT

6.3.2.2.   INITIAL END OF LIFE MODIFIER

The first stage of EoL indicator calculation determines the foundation initial EoL indicator, which is shown in Figure 25 below.
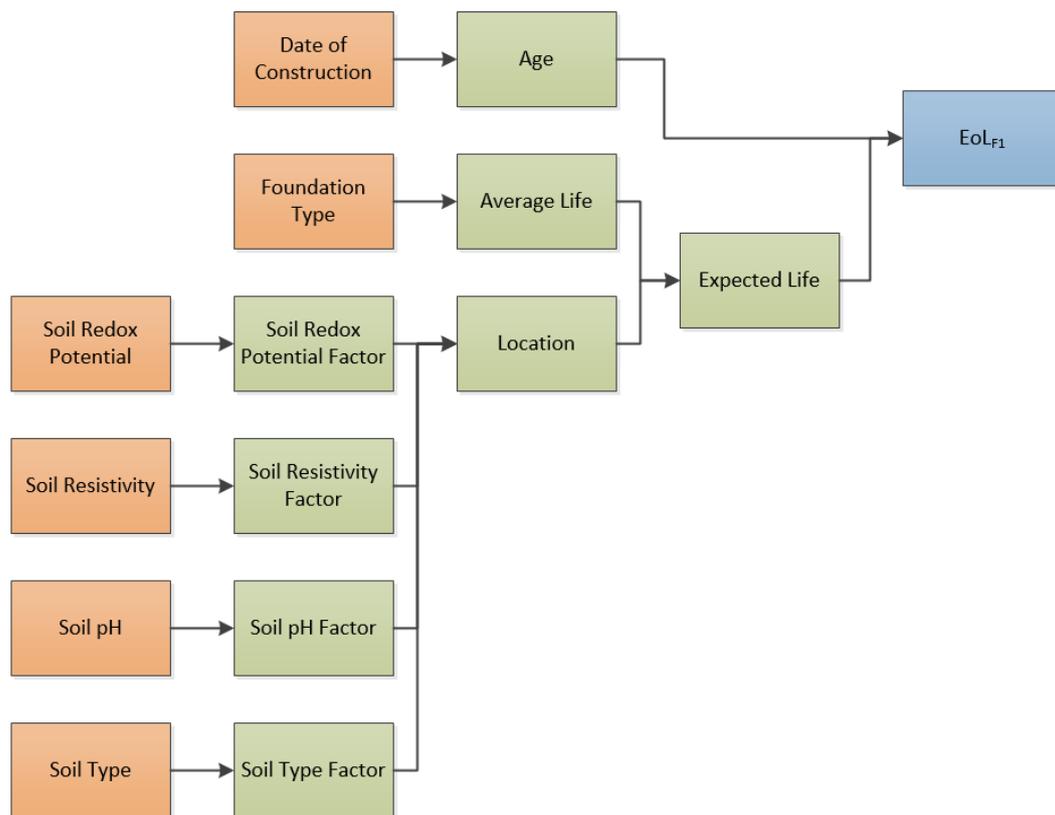
Figure 25 Initial Foundation EoL indicator, EoL$_{F1}$

Soil Resistivity

The resistivity value is simply converted into a score via a calibration table which is then combined with the scores for soil chemistry and redox potential. The combination of these produces a score which is converted into an overall factor when checked with a calibration table.

Soil Chemistry (pH)

The soil pH value is simply converted into a score via a calibration table which is then combined with the scores for soil resistivity and redox potential. The combination of these produces a score which is converted into an overall factor when checked with a calibration table.

Redox Potential

Redox is the process where an oxidisation and reduction reaction occur between 2 different materials that can end up altering some of the key characteristics of that material. When steel rusts the structural integrity of the steel becomes compromised; It expands, becomes more brittle and loses all ductility. These this means the properties useful for steel structures such as a tower are altered which could inevitably lead to failure. The redox value is simply converted into a score via a calibration table which is then combined with the scores for soil resistivity and chemistry. The combination of these produces a score which is converted into an overall factor when checked with a calibration table.

The overall location factor for foundations is either derived from the specific soil test results indicated in Figure 25 or from an overall soil type factor. If neither are available, the factor defaults to a neutral value of 1.

Duty factor is not applicable to tower foundations.

6.3.2.3.   LSE FACTOR

Equation 87

$$LSE = IF(AND(CombinedSoilTestFactor, OverallSoilRatingFactor =), LocationFactorDefault, IF(CombinedSoilTestFactor <>, CombinedSoilTestFactor, OverallSoilRatingFactor))$$

6.3.2.4.   EXPECTED LIFE FACTOR

Starting with the Expected Average Life (L_A), the Duty and LSE factors are used to set an expected life (L_E) for each asset.

Equation 88

$$L_E = \frac{L_A}{F_{LSE} \times F_{DY}}$$

This expected life is then used to determine EoL_1.

The Expected Asset Life is the time (in years) in an asset's life when it would be expected to such deterioration that it is likely to exhibit functional failure. The determination of the L_A considers factors such as original specification and manufacturer data. This corresponds to an EoL Modifier of 5.5.

6.3.2.5.   EOLF1 CALCULATION

The initial EOL modifier is calculated as:

Equation 89

$$EoL_{f1} = \min\left((EoL_{New} \cdot \exp\{\beta_{f1} \cdot Age\}), EoL_{f1,max}\right)$$

Where:

$EoL_{f1, max}$ is 5.5

And $EoL_{f1,i}$ is the Initial Indicator of asset I calculated as:

Equation 90

$$EoL_{f1,i} = EoL_{New} \cdot \exp\{\beta_{f1,i} \cdot Age_i\}$$

where:

$EoL_{f1,i}$ =   Initial Indicator of asset i

EoL_{New} =   Indicator of a new asset (normally set to 0.5)

$\beta_{f1,i}$ =   Initial Ageing Rate of asset i (Section 2.2.1)

The second calculation stage, i.e. to find EoL_2, introduces more specific asset information pertaining to observed condition, inspection surveys, maintenance test results and TOs experience. The possible inputs that can be considered, including the Foundation EoL_1 from the previous calculation stage, are shown below.
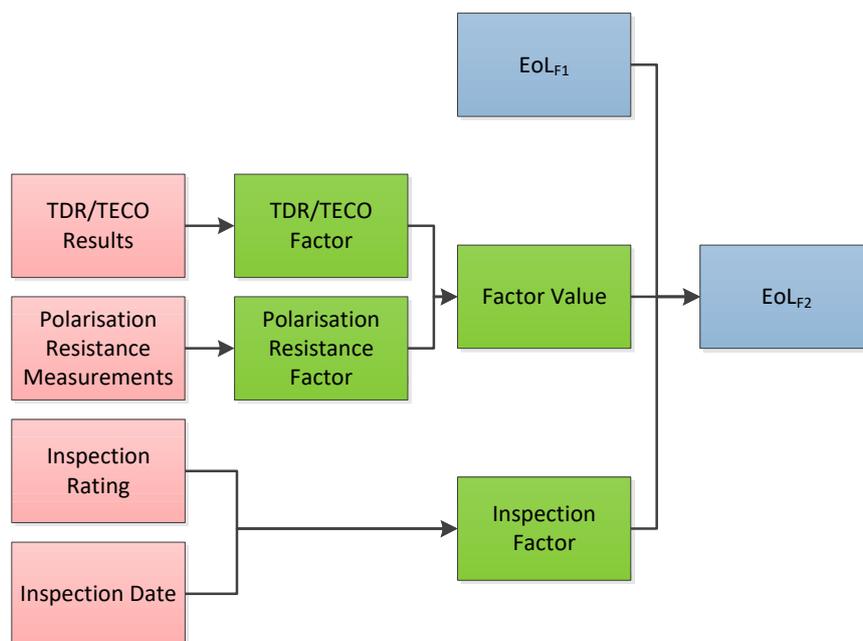
Figure 26 Interim Foundation EoL indicator EoL$_{F2}$

Within this stage of the foundation EoL indicator derivation, the results of asset-specific tests carried out on tower foundations are used to modify the initial foundation EoL indicator.

This interim foundation EoL can be overridden by foundation ratings assigned to foundations which have been excavated and inspected (within defined calibration limits). The override will only take place on the condition that the date at which the excavated rating has been assigned is after the date when the foundation was last routinely inspected/tested. The EoL indicator which results from this mechanism is assigned for the year in which the excavation took place.

Where excavations and repairs have been undertaken, and the date of the completed works is later than the latest date of any condition assessment, then the test data will not be used in the creation of the foundation EoL

indicator. Instead, the EoL indicator will be based upon a calibration value which reflects the EoL of the asset once the repairs have been completed (at the time of completion) and aged to the present year as before.

The Test Data Calibration tables can be found on the Licensee Specific Appendices in the Steel Tower Foundations section.

Overall Factor Value

Equation 91

$$OverallFactorValue = MAX(PolarisationResistanceFactor, TDR/TECOFactor)$$

Where:
PolarisationResistanceFactor = lookup to the calibration tables and is determined the results and ratings of Ecorr and Kcorr tests
TDR/TECOFactor = lookup to the calibration tables and is determined by the results of TDR/TECO tests

6.3.2.7.   FINAL END OF LIFE MODIFIER

EOL at Latest Test Date

Equation 92

$$HIInterimatLatestTestDate = IF\big((EoLf1\ x\ OverallFactorValue) < MinEoL\big), MinEoL, EoLf1\ x\ OverallFactorValue)$$

Foundation MinEoL

Equation 93

$$FoundationMinEoL = MAX(ExcavationFoundationConditionMinEoL, FoundationUnstableMinEoL)$$

Where:
ExcavationFoundationConditionMinEoL = calibration lookup tables based on the condition of the asset
FoundationUnstableMinEoL = yes / no input where the factors are determined by calibration tables in the LSA

EoL Interim Y0

Equation 94

$$EoLInterimY0 = MAX(MIN(EoLInterimatLatestTestDate\ x\ \exp(AgeingConstant\ x\ YearstoY0), FoundationMaxEoL), FoundationMin$$

Where:
YearstoY0 is the Year of the Y0 calculation minus the Latest Test Date

Repair EOL_{Y0}

Equation 95

$$RepairEoLY0 = MAX(MIN(RepairEoLatDate\ x\ \exp(AgeingConstant\ x\ YearsSinceRepair), MaxY0EoL), AsNewEoL)$$

Where:
YearsSinceRepair is the number of years since the repair was carried out
RepairEoLatDate is the EoL of the foundation at the point in which it was repaired

EoLY0

Equation 96

$$EoLY0 = IF(RepairDate < LatestTestDate, EoL\ Interim\ Y0, Repair\ EoLY0)$$

EoLf2

Equation 97

$$EoLf2 = EoLY0\ x\ EoLweighting$$

Where:
EoLweighting is a calibrated lookup value in the LSA

FOUNDATIONS-SPT

6.3.2.8.   INITIAL END OF LIFE INDICATOR, EOL1

The initial End of Life Indicator is based around the age of an asset in relation to the estimated average expected service life which could be reasonably anticipated. This calculation stage does not consider any condition, defect, inspection or testing information, and simply provides an impression of the likely health of an asset given its age and where it is located.

DUTY FACTOR

There is no duty factor calculated for Tower foundations.

LSE FACTOR

The LSE factor for tower foundations is calculated by means of the Overall Location factor as described in the figure below.
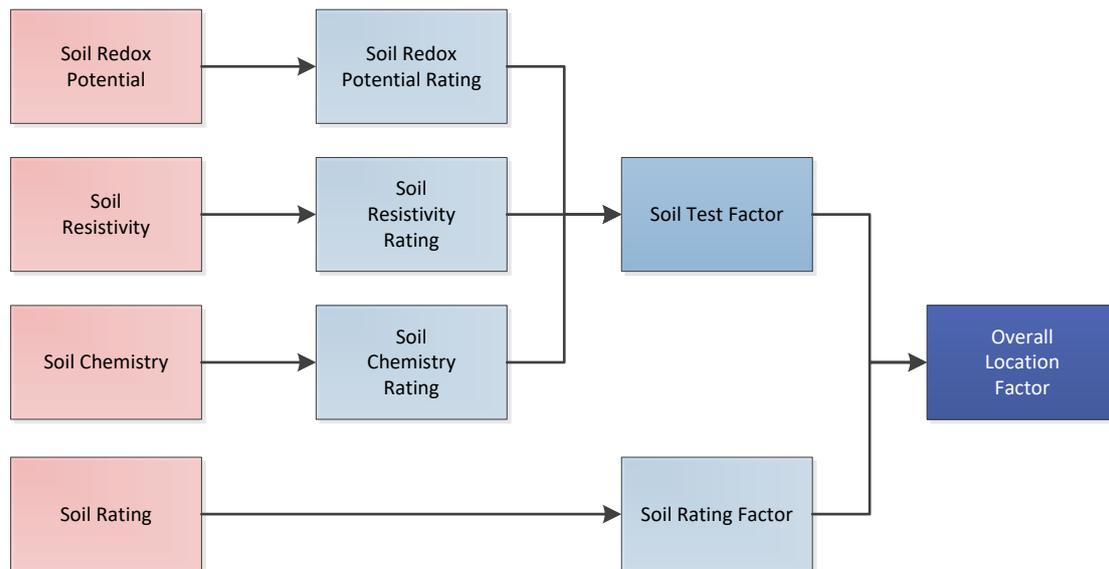
Figure 27 Foundation Overall Location Factor

Soil chemistry (pH), redox potential and soil resistivity are used identify towers at most risk of significant corrosion damage in the future. These values are used to derive individual ratings as per tables as shown in SPT License Specific Appendix.

The combined soil test rating is then calculated as follows:

Equation 98

$$Combined\ Soil\ Test\ Rating = R_{pot} + R_{pH} + R_{res}$$

The combined soil test rating is converted to a Soil Test Factor as per tables as shown in SPT License Specific Appendix.

A separate Soil Rating Factor can be produced for the soil rating. Further details of the implementation can be found in SPT License Specific Appendix.

The Overall Location Factor, F_L, is then derived from the Soil Test Factor if specific soil test results are available, or from the Soil Rating Factor.

EXPECTED LIFE

Starting with the Expected Average Life (L_A), the Duty and LSE factors are used to set an expected life (L_E) for each asset.

Internal Use

Equation 99

$$L_E = \frac{L_A}{F_L}$$

This expected life is then used to determine EoL_1.

EOL1 CALCULATION

The Expected Asset Life is the time (in years) in an asset's life when it would be expected to such deterioration that it is likely to exhibit functional failure. The determination of the L_A considers factors such as original specification and manufacturer data. This corresponds to an EoL Modifier of 5.5.

The calculation of the Overall Location Factor and the calibration values used are described in the equations below.

The initial EOL modifier is calculated as:

Equation 100

$$EoL_1 = \min\left((EoL_{New} \cdot \exp\{\beta_1 \cdot Age\}), EoL_{1,max}\right)$$

Where:

$EOL_{1,\,max}$ is 5.5

And $EoL_{1,i}$ is the Initial Indicator of asset I calculated as:

Equation 101

$$EoL_{1,i} = EoL_{New} \cdot \exp\{\beta_{1,i} \cdot Age_i\}$$

where:

$EoL_{1,i}$ =   Initial Indicator of asset i

EOL_{New} =   Indicator of a new asset (normally set to 0.5)

$\beta_{1,i}$ =   Initial Ageing Rate of asset i (Section 2.2.1)

6.3.2.9.   INTERMEDIATE END OF LIFE INDICATOR, EoL_2

The second calculation stage, i.e. to find EoL_2, introduces more specific asset information pertaining to observed condition, inspection surveys, maintenance test results and operators experience. The inputs are shown in the figure below.
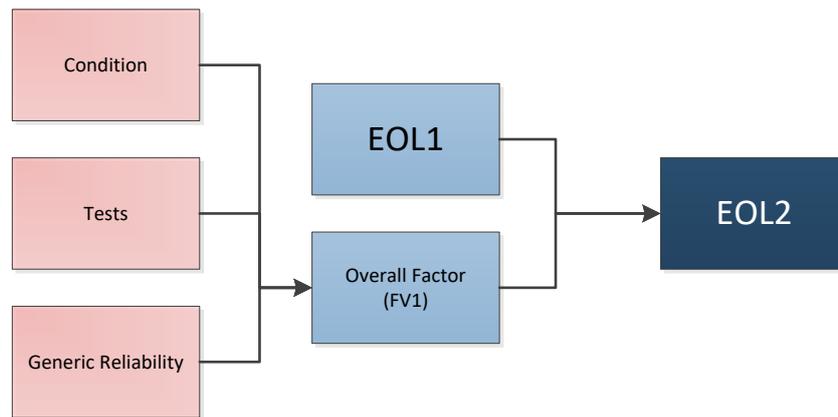
Figure 28 Foundation Intermediate End of Life Indicator EoL_2

CONDITION

The condition factors are combined using the 'Modified Max and Increment' combination method. The Overall Condition Minimum EoL is the maximum of the individual condition minimum EoLs.

TESTS

SP-T have introduced verticality tests to detect towers that have moved out of vertical. A Test Factor and corresponding minimum EoL are derived based on the measured angle of verticality (on a pass/fail basis).

GENERIC RELIABILITY

There are no known reliability issues considered for tower foundations at present.

OVERALL FACTOR VALUE

The overall factor value is derived using the 'Modified Max and Increment' combination method. The inputs and calibration values used to calculate the Overall Factor, FV1, are described in SPT License Specific Appendix. Condition.

6.3.2.10.   FOUNDATION CURRENT END OF LIFE INDICATOR, EOLY0

The derivation of the Current End of Life Indicator can be depicted as shown in the figure below.
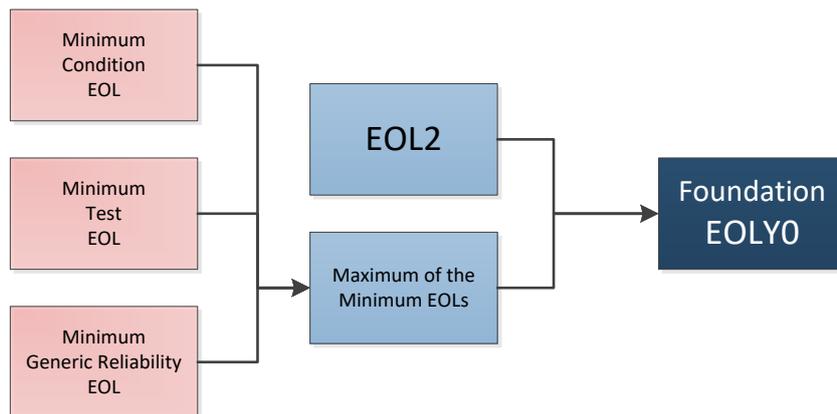
Figure 29 Derivation of the Foundation Current End of Life Indicator, EoL_{Y0}

The foundation EoL_{Y0} the maximum of the EOL2 and Maximum of the Minimum EOLs.

Where excavations and repairs have been undertaken, and the date of the completed works is later than the latest date of any condition assessment, then the test data will not be used in the creation of the foundation health indicator. Instead, the health indicator will be based upon a calibration value which reflects the health of the asset once the repairs have been completed (at the time of completion) and aged to the present year as before.

6.3.3. STEEL TOWER EOL MODIFIER

The Steel Tower EoL indicator is formed from the combination of the Tower Steelwork EoL indicator and the Foundation EoL Indicator, as shown below.
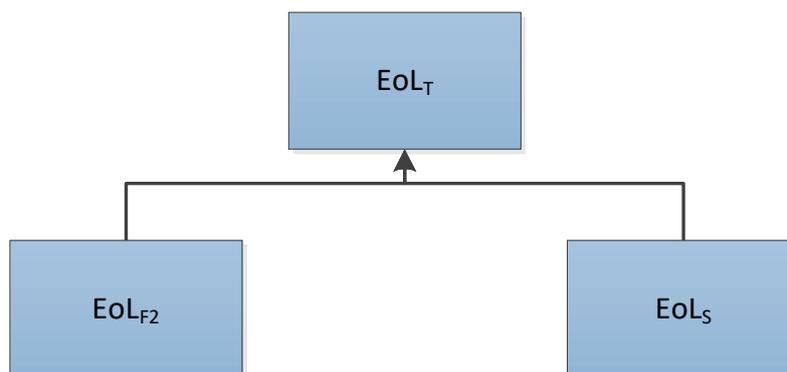
Figure 30 Steel Tower EoL Indicator

Internal Use

SPT- Specific calculation

The tower End of Life Indicator is formed from a combination of a steelwork EoL and a tower foundation End of Life Indicator.

The Tower End of Life Indicator is the largest of the steelwork EoL and foundation EoL as follows:

Equation 102

$$Steel\ Tower\ EoL = max(EoL_{steel}, EoL_{found})$$

where:

EOL_{steel} =   Steelwork End of Life Indicator

EOL_{found} =   Foundation End of Life Indicator

The Current End of Life Indicator of the tower is taken as the maximum of the Current End of Life Indicator of the steelwork and the Current End of Life Indicator of the foundation. Similarly, the Future End of Life Indicator of the tower is taken as the maximum of the Future End of Life Indicator of the steelwork and the Future End of Life Indicator of the foundation.

The derivation of the Steelwork End of Life Indicator and Foundation End of Life Indicator are described in more detail in the following sections.

SSENT- Specific calculation

Once each of the input heath indices have been created, the Steel Tower EoL indicator is formed by taking a weighted average of both the tower steelwork and the foundation EoL indices. This weighted average is subject to a minimum EoL indicator override which is determined by calibration values as per the LSA

Equation 103

$$HIY0Weighting = Sum(WeightedY0EoLSteelwork, WeightedY0EoLFoundations)$$
$$/Sum(SteelworkWeighting, FoundationsWeighting)$$

Equation 104

$$EoLt = IF(OR(EoLs = NULL, EoLf2 = NULL), MinEoLY0, MAX(MinEoLY0, EoLY0Weighting)$$

Where:
MinEoLY0 = the maximum of all minimum EoL's calculated for both steelwork and foundations

Internal Use

7. PROBABILITY OF FAILURE

7.1. PROBABILITY OF FAILURE CALCULATION

The relationship between the condition related probability of failure and time is not linear. An asset can accommodate significant degradation with very little effect on the risk of failure. Conversely, once the degradation becomes significant or widespread, the risk of failure rapidly increases. The use of a standard relationship between PoF and asset health means that End of Life Modifiers for all different types of assets (transformers, cables, switchgear, OHLs) have a consistent meaning. The significance of any individual End of Life Modifier value or the distribution of values for a population can be immediately appreciated. Comparisons between different assets and different asset groups can be made directly.

The method for translating the EoL Value into a probability depends on the asset type. Asset types may need their EoL Modifier translated into an Equivalent Age. The Equivalent Age can then be used to determine probability of failure for a specific end of life failure mode.

The method described here generates an expected end of life modifier function, which is used to map between the EoL modifier and an Equivalent Age. The following paragraph describes how this mapping function can be produced.

The mapping function cannot be generated using historical data points, because the data is right censored since many assets have not completed a whole lifecycle. Judgement needs to be applied about how the health of an asset is expected to deteriorate through its life. The end of life modifier is then mapped to an equivalent age, which is used by FMEA to determine the conditional probability of failure for the corresponding end of life failure mode.

The approach adopted recognises that deterioration and failure results not just from the ageing process but is influenced by events external to the item, e.g. environmental condition or poor installation.

The following two functions were considered as a means of expressing the probability of failure distribution curve mathematically:

- An exponential function, which gives a rapid rise in the probability of failure as the EoL Modifier value increases, i.e. as the deterioration approaches the point of failure.
- A cubic expression (i.e. the first three terms of a Taylor series for an exponential function).

Mathematical modelling[4] using simulated data indicates that the use of an exponential function provides a predicted failure rate that generally falls in the range of the simulated predictions up to about year 15. After this time, the function starts to give predicted failure rates that are too high. A better approach is a hybrid form of the cubic function as shown in Equation 105 [5.] This allows for the probability of failure to be constant for low value End of Life Modifiers (i.e. for assets in good condition) before increasing rapidly as the End of Life Modifier

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[4] "Applying Markov Decision Processes in Asset Management" (M Black) - PhD Thesis, (2003)

[5] "Comparing probabilistic methods for the asset management of distributed items" (M Black, AT Brint and JR Brailsford) - ASCE J. Infrastructure Systems (2005)

increases (i.e. as the item begins to significantly degrade). The cubic function is considered to model asset behaviour more closely than the exponential.

A threshold level (EoL_{lim}, a calibration value) determines the point at which probability of failure is derived using the cubic expression. Up to the limit defined by EoL_{lim}, the probability of failure is set at a constant value; above EoL_{lim} the cubic relationship applies.

Equation 105

$$PoF = k \cdot \left(1 + (EoL \cdot c) + \frac{(EoL \cdot c)^2}{2!} + \frac{(EoL \cdot c)^3}{3!}\right) \text{ where } EoL > EoL_{lim}$$

And

Equation 106

$$PoF = k \cdot \left(1 + (EOL_{lim} \cdot c) + \frac{(EoL_{lim} \cdot c)^2}{2!} + \frac{(EoLI_{lim} \cdot c)^3}{3!}\right) \text{ where } EoL \leq EOL_{lim}$$

where:

PoF	=	probability of failure
EOL	=	End of Life Modifiers
k & c	=	constants
EoL_{lim}	=	EoL Modifier limit below which the probability of failure is constant.

The value of c fixes the relative values of the probability of failure for different modifiers (i.e. the slope of the curve) and k determines the absolute value; both constants are calibration values which are set for each asset class and for each failure mode. Further information on determining the values for c and k is found in Sections 7.2 and 7.3 respectively.

This Process has the benefit of being able to describe a situation where the PoF rises more rapidly as asset condition degrades, but at a more controlled rate than a full exponential function would describe. The End of Life modifier limit (EoL_{lim}) represents the point at which there starts to be a direct relationship between the End of Life modifier and an increasing PoF. The PoF associated with modifiers below this limit relate to installation issues or random events.

7.2.   DETERMINATION OF C

As explained in the Section above, the value of c is set for all Asset Categories and has been initially set such that the PoF for an asset in the worst condition is ten times higher than the PoF of a new asset.

The value of c can be determined by assigning the relative probability of failure values for two EoL Modifier values (generally $EoL = 10$ and $EoL = EoL_{lim}$). Development of the modelling system and experience (gained over twelve years of deployment) with the use of the hybrid EoL / PoF relationship has shown that an appropriate value of c is 1.086; this equates to a ratio of $EoL = 10$ to $EoL = 4$ of approximately 10.

If during the initial calibration or during further experience of operating this methodology this value can be adjusted as necessary.

7.3. DETERMINATION OF K

The values for k (i.e. by failure mode and asset class) are determined using data on historic failure rate data.

The value of k in Equation 107 is derived by consideration of:

- the expected number of functional failures per annum (i.e. across all the failure modes);
- the Indicator distribution for the asset category; and
- the volume of assets in the asset category.

For linear assets, the number of functional failures per kilometre per annum is used in the derivation of k; ie PoF is determined on a per length basis. The calibration process ensures that for each Asset Class, the total expected number of failures of the current asset population matches the number of expected functional failures resulting from the above analysis. Typically, the observed failure rate provides the lower bound for the number of expected functional failures and the number of replaced assets in a given year plus the observed failure rate provides the upper bound.

An estimate of the actual value can be derived from the process itself, by taking the sum of the observed failure rate and the estimated PoF of all replaced assets. The actual value chosen may be derived from expert judgement, preferably supported by analysis of the condition of replaced assets. Where Process-produced failure rates are not supported by direct field evidence, such data should be used as the basis of review and benchmarking wherever possible.

Thus, the value of k is calculated as follows;

Equation 107

$$k \cdot \sum_{i=1}^{n} \left(1 + \text{EoL}_i \cdot c + \frac{(\text{EoL}_i \cdot c)^2}{2!} + \frac{(\text{EoL}_i \cdot c)^3}{3!} \right) = (\text{Expected no. of failures per annum})_I$$

where:

n = the number of assets in asset group I

A calibration table for all of the Values of K used across all failure modes and Lead assets are included in the respective TO's Licensee Specific Appendices.

7.4. CALIBRATION AGAINST VERY LOW OBSERVED FAILURE RATES

The electricity industry recognises that one of the most challenging aspects in modelling the performance of transmission assets is their very high reliability[6]. While there may be numerous records of "defects" or "minor failures", evidence of "major failures" may not exist and the observed failure rate for a particular asset category by particular network TOs may tend towards zero. This potentially leads to an inaccurate determination of asset condition risk.

Given this widely-recognised problem (and the resulting lack of data available to each Transmission Owner), the IEC White Paper on "Strategic asset management of power networks"[7] recommends that "a standardized set of functions to which to fit historical data could be specified, together with a method for determining which particular function to use for a given data set, considering environment and load conditions. This would dramatically improve the accuracy of service life estimation across businesses and allow benchmarking and comparison of various approaches". This is the approach taken by in this Process, but it is of course dependent on the effective exchange of industry-wide data to enable effective calibration and benchmarking.

Fortunately, such exchanges do exist, including industry-wide reliability assessments, such as EPRI's Industry-Wide Substation Equipment Performance and Failure Database[8] or UMS's International Transmission Operations & Maintenance Study[9]. Where failure rates are not supported by direct field evidence, such data should be used as the basis of review and benchmarking wherever possible.

The values of k by asset class and failure mode are presented in Licensee Specific Appendices. These values have been calculated using historic failure rates (where available). Where no failures have occurred over this time-period, it is necessary to estimate the "expected" failure rate as described above.

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[6] Section 5.1.3 of CIGRE TB 422 Transmission Asset Risk Management (August 2010)
[7] http://www.iec.ch/whitepaper/pdf/iecWP-assetmanagement-LR-en.pdf
[8] http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001020010
[9] http://www.umsgroup.com/Americas/What-we-do/Learning-Consortia/ITOMS

8.   CONSEQUENCE OF FAILURE

The consequences of the failure may fall into four categories:

Consequence	Description
System	The impact on the network of the failure and any subsequent intervention required
Safety	Impact of direct harm to public/personnel as a result of failure mode
Environment	Impact of failure mode taking into account the sensitivity of the geographical area local to the asset
Financial	Cost of the intervention needed to address and resolve the failure

Table 4 Types of Consequence of failure

These categories reflect the impact of the various failure modes which are specific to the asset and the consequences are consistent for each class of failure mode. The impact of the various failure modes will vary depending on the type of failure. For example, for less disruptive failure modes there may be no impact from a safety perspective.

Safety and environmental consequence are specific to the asset and to its physical location.

In considering the safety and environment consequences, the concept of exposure is needed. Exposure is based upon the asset's location, i.e. its proximity to a location where it has the potential to cause harm (whether to people or the environment).

Each consequence will be monetised and the price base for consequence of failure will be agreed with Ofgem although TO's should be able flex around the agreed position where it is reasonably justified to do so.

Failure Modes, Effects and Criticality Analysis (FMECA) is an extension of the FMEA to include a means of ranking the severity of the failure modes to allow prioritisation of countermeasures. BS EN60812 disaggregates systems into their component parts and assesses the probability of functional failures of each component and the consequences of such functional failures, then aggregates these quantities to obtain an estimate of the overall risk of the system. A failure mode is clearly immaterial if the cost of the analysis of the functional failure of a component is much greater than value of the risk represented by the functional failure of that component, because either the probability of functional failure of a component or the consequence of failure of a component is insufficiently large.

Evidential and supporting data, suitable for FMECA analysis is usually imperfect. Some possible effects and consequences might be material, but have not yet occurred. Similarly, accurate data may not have been captured for failures, even though the effects and consequences have occurred. Effective application of FMECA therefore requires engineering judgement, both to envision material consequences that have not yet occurred and to estimate values which have not been measured and / or recorded and which cannot be reliably calculated from first principles.

It is the aim of this section to provide a quantified view of a monetised consequence. The quantification of each of the consequences below forms an approximation to how this may play out in the real world. In this case an approximation is of much greater value, due to its simplified nature and the ease of comparison and benchmark.

The monetisation does not correspond to the actual costs that will be incurred. The data used in the models attempts to approach the correct orders of magnitude to avoid confusion it does not however, guarantee this and can only be treated as abstract.

8.1.   SYSTEM CONSEQUENCE

The system consequence of a Failure or Failure Mode Effect of an asset is an indication of the asset's importance in terms of its function to the transmission system as given by the disruption to that function caused by the failure. It is measured in terms of certain system related costs incurred by the industry electricity sector if that asset was to experience a failure. These system costs can be divided into two categories, customer costs and System Operator (SO) costs. Regardless of who initially pays these costs they are ultimately born by electricity consumers. Customer costs are incurred as a result of the disconnection of customers supplied directly or indirectly (via a distribution network) by the transmission system. The cost for demand disconnections are expressed as the economic value that the user assigns to that lost load. In the case of generators being disconnected from the network there is a mechanism of direct compensation payments from the SO. The second category of costs are those that the SO incurs in undertaking corrective and preventative measures to secure the system after asset failures have occurred. These include generator constraint payments, response and reserve costs and auxiliary services costs.

Unlike the environmental, financial and safety consequences of asset failures, the existence and scale of network risk due to asset failures is dependent on the functional role that the failed asset plays in the transmission system. The transmission system is designed with a degree of resilience that seeks to ensure the impact of asset faults is contained within acceptable limits. The National Electricity Transmission System Security and Quality of Supply Standard (NETS SQSS) mandates a certain level of resilience that the design and operation of the transmission system must meet when faced with a range of scenarios and events. It is a License obligation of TO's that their networks comply with the NETS SQSS.

A range of negative system consequences (unacceptable overloading of primary transmission equipment, unacceptable voltage conditions or system instability) must be avoided for 'defined secured events' under certain network conditions. The required resilience is not absolute nor is it uniform across the network. The philosophy behind the NETS SQSS is that lower severity consequences are acceptable for relatively high probability (and therefore high frequency) faults while more severe consequences are only to be accepted for lower probability events. Figure 31 illustrates this philosophy.

This approach is further influenced by other considerations such as the geographical location of the assets in question, i.e. which TO License Area they're in, and for what timescales the network is being assessed (near term operational timescales vs. Long term planning timescales). The level of resilience required also varies depending on the function of the part of the network in question. Parts of the network which connect demand, generation or make up part of the Main Interconnected Transmission System (MITS) all have distinct design requirements dependent upon their importance to the Transmission System and the total economic value of all the customers they supply.
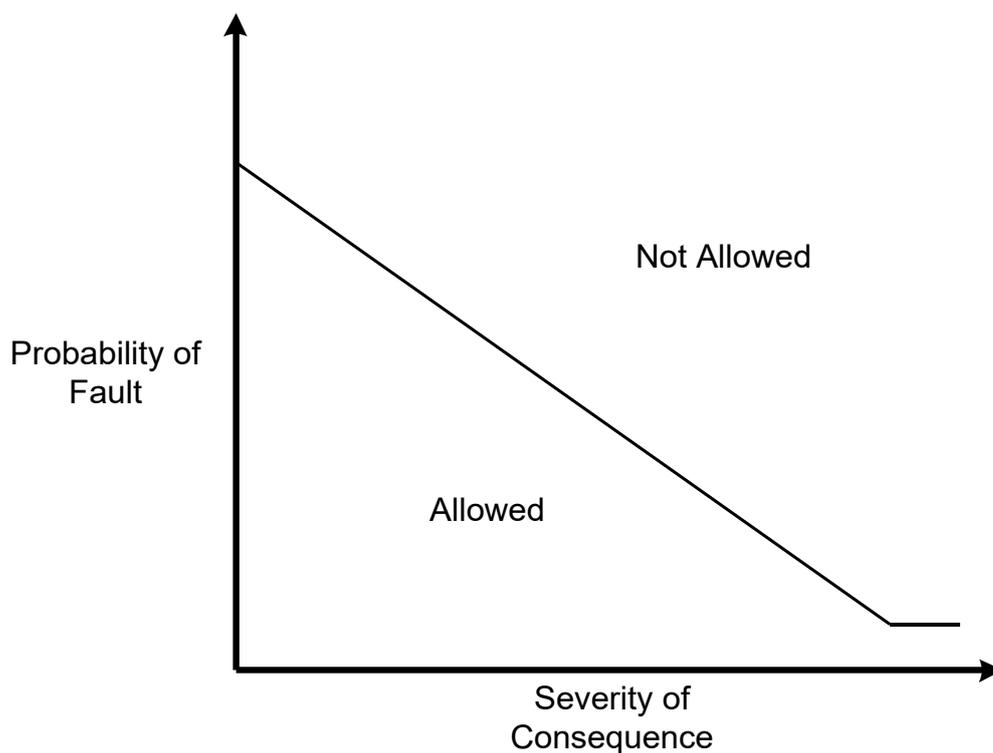
Figure 31 Graph of Allowable Severity against Probability of fault

Events that the NETS SQSS requires a degree of resilience against are described as 'secured events'. These are events that occur with sufficient frequency that it is economic to invest in transmission infrastructure to prevent certain consequences when such events occur on the system. Secured events include faults on equipment and these events range from single transmission circuit faults (highest frequency) to circuit breaker faults (lowest frequency). When an asset fault occurs that results in the loss of only a single transmission circuit in an otherwise intact network, almost no customer losses are permitted and all system parameters must stay within limits without the SO taking immediate post-fault actions. While in the case of circuit breaker faults the NETS SQSS only requires that the system is planned such that customer losses are contained to the level necessary to ensure the system frequency stays within statutory limits to avoid total system collapse.

The key assumption that underpins this variation in permitted consequences of faults is that most faults are weather related and that faults caused by the condition of the asset are rare. This can be seen in that faults on overhead lines (often affected by wind and lightning) are relatively frequent events (≈20% probability per 100 km 400 kV circuit per annum) while switchgear faults are relatively less frequent (≈2% probability per 2-ended 400 kV circuit per annum). Another key assumption in the design of the SQSS is that faults are relatively short. A clear majority of circuits have a post-fault rating that is time limited to 24 hours, it is expected that faults will be resolved within this time so that this rating will not be exceeded.

Asset failures driven by asset condition do not conform to these key assumptions, they occur in assets regardless of their exposure to the elements and they can significantly exceed 24 hours in duration. The system therefore cannot be assumed to be designed to be resilient against even a single asset failure. Even if system resilience is sufficient to avoid an immediate customer or operator cost, no asset fault or failure that requires offline intervention can be said to be free from a risk cost. At the very least, the unavailability of the asset reduces system resilience to further events and therefore increases exposure to future costs.

8.1.1. QUANTIFYING THE SYSTEM RISK DUE TO ASSET FAULTS AND FAILURES

Fundamentally the transmission system performs three functions. It receives power from generators, transports power where it is needed and delivers it to consumers. The system risk cost of a fault or failure can be quantified by combining the following costs:

1. The economic value assigned to load not supplied to consumers including directly connected demand customers. Commonly described as Value of Lost Load (VOLL) in units of £/MWh

2. The cost of compensating generators disconnected from the transmission system, based on the market cost of generation (£/MWh), the size of the generator (MW) and the expected duration of disconnection (hours)

3. The cost of paying for other generators to replace the power lost from disconnected generation based on the market cost of replacement generation (£/MWh) and number of megawatt hours that require replacement

4. The increased cost in transporting power across the wider transmission network. This is comprised of:

    a. Constraint payments to generators due to insufficient capacity in part of the transmission system. This comprises the costs to constrain off generation affected by the insufficient capacity and the cost to constrain on generation to replace it. If there is insufficient replacement generation capacity, costs will include demand reduction.
    b. Payments to generators to provide auxiliary services which ensure system security and quality of supply e.g. the provision of reactive power.

The applicability and size of these cost sources are dependent upon the role of the failed asset in the system. Some assets are solely for the connection of generation or demand, while others will provide multiple functions.

The methodology for calculating these potential costs is split into three parts:

A. A customer disconnection methodology, incorporating the cost of disconnecting generation, total consumer demand and vital infrastructure sites (1, 2 and 3 above)
B. A boundary transfer methodology that estimates potential generator constraint payments (4a)
C. A reactive compensation methodology that estimates the cost of procuring reactive power to replace that provided by faulted assets (4b)

Each of these methodologies will be described in turn in the following sections. All three share a common structure that can be expressed by Equation 108.

Equation 108

$$Cost\ of\ System\ Impact\ = probability\ \ x\ duration\ x\ size\ x\ cost\ per\ unit$$

The total cost of system impact of a Failure Mode of an asset will be the sum of the consequence costs that come from the three above costs.

8.1.2. CUSTOMER DISCONNECTION – CUSTOMER SITES AT RISK

Except for radial spurs, assets on the system will usually contribute towards the security of more than one substation that connects customers to the network. However, the fewer other circuits that supply a substation, the more important that asset is for the security of the site. In order to identify which sites are most at risk of disconnection because of the failure of a specific asset, the number of circuits left supplying a customer connection site after a failure of an asset, X, is defined;

Equation 109

$$X = number\ of\ parallel\ circuits\ supplying\ customer\ site(s)$$
$$-\ number\ of\ circuits\ tripped\ as\ a\ result\ of\ the\ Failure\ Mode\ Effect\ of\ the\ asset$$

Circuit availability statistics indicate that the importance of a circuit decreases by around two orders of magnitude for each extra parallel circuit available. Given that the uncertainty of other inputs into these calculations will be greater than 1% it is a reasonable simplification to neglect all customer sites with values of X greater than the minimum value of X; $X_{min}=min(X)$.

Once there are four or more circuits in parallel supplying a site additional circuits do not necessarily decrease the probability of losing customers as the capacity of the remaining circuits will not be sufficient to meet the import/export of the customers at risk. In parts of the network where the number and rating of circuits connecting a substation are determined solely by the need to meet local demand, there is a significant risk that once two or three circuits have been lost cascade tripping of remaining circuits due to overloading will result.

Therefore:

For assets on circuits containing transformers down to 132 kV or below if $X_{min} > 3$ it will be treated as $X_{min} = 3$ for the purposes of calculating the Probability of Disconnection (P_{oc}) and Duration (D).

Otherwise for assets on circuits at 275 kV or below if $X_{min} = 4$ it will be treated as $X_{min} = 3$ for the purposes of calculating the Probability of Disconnection (P_{oc}) and Duration (D).

Otherwise if $X_{min} > 3$ then the risk of customer disconnection will be neglected as negligible.

As there will often be multiple customer connection sites with $X=X_{min}$, to ensure that the methodology is efficient and operable a variable Z, is introduced which is equal to the number of customer sites with $X=X_{min}$ for a given asset. Only the largest group of customer sites that would be disconnected by the loss of a further X_{min} circuits is considered explicitly while the extra risk of customer disconnection due to other combinations of circuit losses is approximated by the use of the risk multiplier coefficient M_Z:

Equation 110

$$M_Z = \frac{\sum Z + (Z-1) + (Z-2) + \dots}{Z}$$

Intuitively $M_1 = 1$, and M_Z scales with increasing values of Z. **Figure** illustrates an example of how M_Z is calculated with three customer sites (M_3):
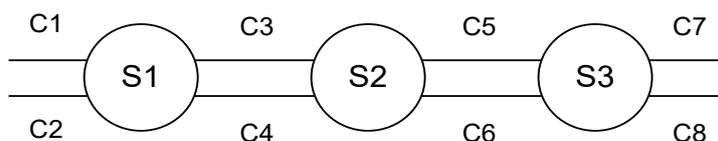
<p align="center">**Figure 25**</p>

Three substations labelled S1, S2 and S3 are part of a double circuit ring with eight circuits labelled C1-C8. Each substation is immediately connected to the rest of the system by four circuits and could be disconnected from the system if these four immediate circuits were lost. However, each substation could also be disconnected by other combinations of four circuit losses also. For example, S2 could be disconnected by the loss of C3, C4, C5 and C6, but also by losing C3, C4, C7 and C8 or C1, C2, C5 and C6 etc. More than one substation would be lost for these other combinations and all three substations would be lost for a loss of C1, C2, C7 and C8.

In order to calculate the total system consequence of a failure mode of an asset that is part of C1 we assume that the volume and cost per unit of customer connections are approximately evenly distributed among the substations (L for each substation) and that the probability (P) and duration (D) of each four-circuit combination being lost is approximately equal. The relative consequence of a loss event is then determined only by the number of customers lost. So a loss of S1 and S2 is twice the consequence of losing only S1. There is one combination of four circuit losses involving C1 that disconnects a single substation, one combination that disconnects two substations and one that disconnects all three. Therefore, the risk cost is:

Equation 111

$$Risk\ cost = (1 \times PDL) + (1 \times 2PDL) + (1 \times 3PDL) = 6\ PDL$$

Given the risk cost of losing all three sites at once is 3PDL so the risk cost can be expressed as a function of the risk cost of losing all three sites at once:

Equation 112

$$Risk\ cost = 6\ PDL = 2 \times 3PDL = 3PDLM_3$$

Therefore, M_3 is equal to 2.

8.1.3. CUSTOMER DISCONNECTION − PROBABILITY

The probability of a generator or consumer being disconnected because of an asset failure is a function of a wide range of variables including the physical outcome of the failure, the local network topology, asset composition of circuits, asset loading, physical proximity of assets, protection configuration and operation options for restoration. The probability of consequence is calculated as a function of five probabilities, shown in Table 5.

Probability	Symbol	Determination of Value
Coincident outage	P_o	TO statistics on planned unavailability of circuits
Damage to another circuit	P_d	TO historical experience of explosive/incendiary failure modes
Maloperation of another circuit	P_m	TO statistics on protection maloperation
Coincident fault to another circuit	P_f	TO fault statistics
Overloading of remaining circuit	P_l	TO specific network design

Table 5 Functions of Probability of Consequence

The probabilities P_o, P_d, P_m and P_f are determined separately by each TO according to their own methodology outlined in Licensee Specific Appendices.

The probabilities in Table 5 can be combined to create a probability tree for each value of X_{min} between 0 and 3. Below are the resulting equations for P_{oc}, the probability of disconnection.

Equation 113

$$\text{For } X_{min} = 0, P_{oc} = 1$$

Equation 114

$$\text{For } X_{min} = 1, P_{oc} = P_d + N_d P_o + N_o N_d P_m + N_o N_d N_m P_f$$

Equation 115

For $X_{min} = 2$, $P_{oc} = P_d^2 + 2P_d N_d P_o + 2P_d N_d N_o P_m + 2P_d N_d N_o N_m P_f + N_d^2 P_o P_m + N_d^2 P_o N_m P_f + N_d^2 N_o P_m P_f + N_d^2 N_o N_m P_f^2$

Equation 116

For $X_{min} = 3$, $P_{oc} = P_d^2 P_o + P_d^2 N_o P_m + P_d^2 N_o N_m P_f + P_d^2 N_o N_m N_f P_l + 2P_d N_d P_o P_m + 2P_d N_d P_o N_m P_f + 2P_d N_d P_o N_m N_f P_l + 2P_d N_d N_o P_m P_f + 2P_d N_d N_o P_m N_f P_l + 2P_d N_d N_o N_m P_f^2 + 4P_d N_d N_o N_m P_f N_f P_l + N_d^2 P_o P_m P_f + N_d^2 P_o P_m N_f P_l + N_d^2 P_o N_m P_f^2 + 2N_d^2 P_o N_m P_f N_f P_l + N_d^2 N_o P_m P_f^2 + 2N_d^2 N_o P_m P_f N_f P_l + N_d^2 N_o N_m P_f^3 + 3N_d^2 N_o N_m P_f^2 N_f P_l$

Where N_o, N_d, N_m, N_f and N_l are the probabilities of no outage, no damage, no maloperation, no coincident faults and no overloading respectively.

The derivation method of the above probability equations can be followed in Figure 32, the probability tree diagram for the most complex of the four cases, X_{min} = 3.

Initial pre-failure network state

Asset Experience Failure Mode

3 circuits remaining

Asset Failure damages asset on two parallel circuits (P_d^2)

1 circuit remaining

Probability of parallel outage (P_o)

0 circuits remaining ($P_d^2 P_o$)

Probability of no parallel outage (N_o)

1 circuit remaining

Probability of Maloperation (P_m)

0 circuits remaining ($P_d^2 N_o P_m$)

Probability of no Maloperation (N_m)

1 circuit remaining

Probability of unrelated fault (P_f)

0 circuits remaining ($P_d^2 N_o N_m P_f$)

Probability of no unrelated fault (N_f)

1 circuit remaining

Probability of overloading circuit (P_l)

0 circuits remaining ($P_d^2 N_o N_m N_f P_l$)

Asset Failure damages asset on one parallel circuit ($2PdN_d$)

2 circuits remaining

Probability of parallel outage (P_o)

1 circuit remaining

Probability of Maloperation (P_m)

0 circuits remaining ($2P_d N_d P_o P_m$)

Probability of no Maloperation (N_m)

1 circuit remaining

Probability of unrelated fault (P_f)

0 circuits remaining ($2P_d N_d P_o N_m P_f$)

Probability of no unrelated fault (N_f)

1 circuit remaining

Probability of overloading circuit (P_l)

0 circuits remaining ($2P_d N_d P_o N_m N_f P_l$)

Probability of no parallel outage (N_o)

2 circuits remaining

Probability of Maloperation (P_m)

1 circuit remaining

Probability of unrelated fault (P_f)

0 circuits remaining ($2P_d N_d N_o P_m P_f$)

Probability of no unrelated fault (N_f)

1 circuit remaining

Probability of overloading circuit (P_l)

0 circuits remaining ($2P_d N_d N_o P_m N_f P_l$)

Probability of no Maloperation (N_m)

2 circuits remaining

Probability of two unrelated faults (P_f^2)

0 circuits remaining ($2P_d N_d N_o N_m P_f^2$)

Probability of no second unrelated fault ($2P_f N_f$)

1 circuit remaining

Probability of overloading circuit (P_l)

0 circuits remaining ($4P_d N_d N_o N_m P_f N_f P_l$)

Asset Failure damages no assets on parallel circuits (N_d^2)

Continued Below

Continued

3 circuits remaining

Probability of
parallel outage (P_o)

2 circuits remaining

Probability of
Maloperation
(P_m)

1 circuit remaining

Probability of
unrelated fault
(P_f)

0 circuits remaining
$(N_d{}^2 P_o P_m P_f)$

Probability of
no parallel
outage (N_o)

Probability of no
maloperation (N_m)

Probability of no
unrelated fault (N_f)

1 circuit remaining

Probability of
overloading
circuit (P_l)

0 circuits remaining
$(N_d{}^2 P_o P_m N_f P_l)$

2 circuits remaining

Probability of two
unrelated faults
$(P_f{}^2)$

0 circuits remaining
$(N_d{}^2 P_o N_m P_f{}^2)$

Probability of no
second unrelated
fault $(2P_f N_f)$

1 circuit remaining

Probability of
overloading
circuit (P_l)

0 circuits remaining
$(2N_d{}^2 P_o N_m P_f N_f P_l)$

3 circuits remaining

Probability of
Maloperation
(P_m)

2 circuits remaining

Probability of two
unrelated faults
$(P_f{}^2)$

0 circuits remaining
$(N_d{}^2 N_o P_m P_f{}^2)$

Probability of no
maloperation (N_m)

Probability of no
second unrelated
fault $(2P_f N_f)$

1 circuit remaining

Probability of
overloading
circuit (P_l)

0 circuits remaining
$(2N_d{}^2 N_o P_m P_f N_f P_l)$

3 circuits remaining

Probability of
three unrelated
faults $(P_f{}^2)$

0 circuits remaining
$(N_d{}^2 N_o N_m P_f{}^3)$

Probability of two
unrelated faults
$(3P_f P_f N_f)$

1 circuit remaining

Probability of
overloading
circuit (P_l)

0 circuits remaining
$(3N_d{}^2 N_o N_m P_f{}^2 N_f P_l)$

Figure 32 Probability Tree Diagram for Xmin = 3

8.1.4. CUSTOMER DISCONNECTION – DURATION

A similar approach is taken with the expected duration of such a disconnection event. This is dictated by the failure mode of the asset in question, and both operational and asset interventions available to restore supply to the customers. To calculate the duration of disconnection, six separate durations are introduced in Table 6.

Duration	Symbol	Determination of Value
Duration of failure mode unavailability	D_{fm}	TO experience of failure durations
Outage restoration time	D_o	TO statistics on planned unavailability of circuits
Circuit damage restoration time	D_d	TO historical experience of explosive/incendiary failures of failure mode
Protection mal-operation restoration time	D_m	TO statistics on protection maloperation
Unrelated fault restoration time	D_f	TO fault statistics
Circuit overload restoration time	D_l	TO historical experience of overload trips

Table 6 Duration of Consequence

The durations D_{fm}, D_o, D_d, D_m and D_f are determined separately by each TO per their own methodology outlined in Licensee Specific Appendices.

The duration of customer loss is calculated by weighting the probabilities of the event combinations outlined in the formulae for P_{oc} and multiplying by the shortest of the above durations that apply to that event combination. For example, if a failure mode with X_{min} = 2 and disconnection is due to a combination of the failure mode, a parallel outage and protection mal-operation then the minimum of D_{fm}, D_o and D_m is weighted with the other minimum durations of other disconnection combinations. Below are the equations for D for different values of X_{min}.

Equation 117

For $X_{min} = 0$, $D = D_{fm}$

Equation 118

For $X_{min} = 1$, $D = [min(D_{fm}, D_d)P_d + min(D_{fm}, D_o)N_d P_o + min(D_{fm}, D_m)N_o N_d P_m + min(D_{fm}, D_f)N_o N_d N_m P_f] / Poc$

Equation 119

For $X_{min} = 2$, $D = [min(D_{fm},D_d)P_d^2 + min(D_{fm}, D_d, D_o)2P_dN_dP_o + min(D_{fm},D_d,D_m)2P_dN_dN_oP_m + min(D_{fm},D_d,D_f)2P_dN_dN_oN_mP_f + min(D_{fm},D_o,D_m)N_d^2P_oP_m + min(D_{fm},D_o,D_f)N_d^2P_oN_mP_f + min(D_{fm},D_m,D_f)N_d^2N_oP_mP_f + min(D_{fm},D_f)N_d^2N_oN_mP_f^2] / P_{oc}$

Equation 120

For $X_{min} = 3$, $D = [min(D_{fm},D_d,D_o)P_d^2P_o + min(D_{fm},D_d,D_m)P_d^2N_oP_m + min(D_{fm},D_d,D_f)P_d^2N_oN_mP_f + min(D_{fm},D_d,D_l)P_d^2N_oN_mN_fP_l + min(D_{fm},D_d,D_o,D_m)2P_dN_dP_oP_m + min(D_{fm},D_d,D_o,D_f)2P_dN_dP_oN_mP_f + min(D_{fm},D_d,D_o,D_l)2P_dN_dP_oN_mN_fP_l + min(D_{fm},D_d,D_m,D_f)2P_dN_dN_oP_mP_f + min(D_{fm},D_d,D_m,D_l)2P_dN_dN_oP_mN_fP_l + min(D_{fm},D_d,D_f)2P_dN_dN_oN_mP_f^2 + min(D_{fm},D_d,D_f,D_l)4P_dN_dN_oN_mP_fN_fP_l + min(D_{fm},D_o,D_m,D_f)N_d^2P_oP_mP_f + min(D_{fm},D_o,D_m,D_l)N_d^2P_oP_mN_fP_l + min(D_{fm},D_o,D_f)N_d^2P_oN_mP_f^2 + min(D_{fm},D_o,D_f,D_l)2N_d^2P_oN_mP_fN_fP_l + min(D_{fm},D_m,D_f)N_d^2N_oP_mP_f^2 + min(D_{fm},D_m,D_f,D_l)2N_d^2N_oP_mP_fN_fP_l + min(D_{fm},D_f)N_d^2N_oN_mP_f^3 + min(D_{fm},D_f,D_l)3N_d^2N_oN_mP_f^2N_fP_l]/ P_{oc}$

8.1.5. CUSTOMER DISCONNECTION – SIZE AND UNIT COST

Once the largest group of customer sites with $X = X_{min}$ for a given failure mode of an asset has been identified the size of consequence of disconnection of this group must be fully quantified. The weighted quantity of generation disconnected, MW_W is given by:

Equation 121

$$MW_W = \sum \varphi MW_{GTEC}$$

Where MW_{GTEC} is the Transmission Entry Capacity (TEC) of each disconnected generator and φ is the design variation weighting factor. This factor equals 1 for generators who are connected with standard SQSS levels of security. Its value for generators with lower than standard levels of security will be determined by each TO. TEC is used without any reference to load factor as this is how generator disconnection compensation is calculated as laid out in the Connection and Use of System Code (CUSC). Secondly the annual average true demand of customers disconnected, MW_D, is calculated by summing the peak demand and the embedded generation contribution during peak of all sites at risk. Both the peak demand and contribution of embedded generation is taken directly from DNO week 24 data submissions. The final inputs are the number of vital infrastructure sites of three different types supplied by sites at risk as shown in Table 7. These are demand sites of particular importance in terms of economic or public safety impact. There is no additional quantification of the risk of disconnection of customers or consumers for which the disconnection risks are considered High Impact Low Probability (HILP) events. The risk is treated on a per MW basis like any other consumer or customer.

The lists of sites that belong to the categories outlined in Table 7 are deemed sensitive and thus are not included here. The selection criteria and sources for the lists of sites can be found in the individual TO specific appendices. The costs of disconnection per site, per hour were calculated by collecting as much publicly available information as possible on the costs of historic disconnection events of comparable infrastructure

sites across the developed world. These costs per hour or per event were converted into current sterling prices through exchange rate and price indexation conversion. An average for each category was then taken.

Vital Infrastructure Category	Symbol and Cost		
	Number of Sites	Cost per site per hour (£/hr)	Cost per site per disconnection event (£)
Transport Hubs	S_T	V_T	-
Economic Key Point	S_E	V_E	-
Particularly sensitive COMAH sites	S_C	-	V_C

Table 7

The values for V_T, V_E and V_C are contained within the Licensee Specific Appendices.

The final component of the risk cost, the per unit cost, is separately defined for the three above quantities of customer loss. *VOLL* in £/MWh is the same RPI indexed value as that used in the RIIO-T1 energy not supplied incentive (see Licensee Specific Appendix for value)

The cost of disconnection of generation is in two parts, firstly the generation compensation payment cost, G_C, in £/MWh varies with outage duration is based upon the CUSC methodology and uses cost information from System Operator.

Equation 122

$$\text{For D} \leq 1.5\text{h}, \; G_c = MW_W D C_{SBP}$$

Equation 123

$$\text{For 1.5 h} < \text{D} \leq 24\text{h}, \; G_c = MW_W(1.5 C_{SBP} + \{D - 1.5\}C_{SMP})$$

Equation 124

$$\text{For D} > 24\text{h}, \; G_c = MW_W(1.5 C_{SBP} + 22.5 C_{SMP} + \{D - 24\}C_{TNUoS})$$

Where C_{SBP} is the annual average system buy price in £MWh^{-1}, C_{SMP} is the annual average system marginal price in £MWh^{-1} and C_{TNUoS} is the average Transmission Network Use of System (TNUoS) refund cost per MW per hour. C_{TNUoS} is calculated by divided the annual TNUoS charge for all generators by the total of TEC of all generators and again by 8760.

Secondly, the cost of generation replacement, G_{R*}, again dependent on D is defined as below.

Equation 125

$$\text{For D} \leq \text{2h, } G_R = D C_{SMP}(0.42MW_W - 0.62MW_D)$$

Equation 126

$$\text{For D} > \text{2h, } G_R = 2C_{SMP}(0.42MW_W - 0.62MW_D)$$

Equation 127

$$\text{For } G_R \geq 0, G_{R*} = G_R$$

Equation 128

$$\text{For } G_R < 0, G_{R*} = 0$$

This cost reflects the expense of the System Operator constraining on generation to replace that lost by the disconnection of generation. The equation multiples the duration of the disconnection and the annual average price to constrain on plant by the mismatch between the expected mismatch between generation and demand disconnected by the event. This mismatch is calculated by first taking the total TEC of generation connected to the customer sites in the group at risk, MW_W, and multiplying it by the system wide average generation load factor 0.42 (calculated by dividing the total energy generated in a year in MWh across the whole system by 8760 and then by the total TEC of all generation on the system). Secondly the peak adjusted demand, MW_D, of all customer sites in the group is multiplied by the average demand factor 0.62 (calculated by dividing the total annual transmission demand in MWh by 8760 and dividing again by the winter peak demand in MW). The difference between these two numbers is the mismatch, multiplied by the System Marginal Price in £MWh^{-1} and the duration up to a maximum of 2 hours. After 2 hours, it would be expected that the market would have self-corrected for the generation mismatch.

The vital infrastructure site disconnection cost, V, is the numbers of different types of vital infrastructure sites multiplied by the cost per site and in the case of transport and economic key point sites multiplied by D.

Equation 129

$$V = D(V_T S_T + V_E S_E) + V_C S_C)$$

With all elements of the equation defined, the customer disconnection risk cost, $R_{customer}$, of a given asset failure mode of any asset can be defined by Equation 130.

Equation 130

$$R_{customer} = P_{oc}[G_C + G_R + 0.62 DMW_D VOLL + V]M_z$$

A vast majority of lead assets will return a non-zero value for customer disconnection risk, the exceptions being shunt reactors and circuits which connect nodes with more than 4 circuits. These assets will have material risks for one of the next two elements of system consequence.

Note that in the future it may be possible to vary VOLL with the type of load lost but this is not included in the current methodology.

8.1.6. BOUNDARY TRANSFER

This methodology estimates the cost impact of having to pay generation constraint payments in order to restrict flows across a system boundary. Unlike the customer disconnection methodology, there is not a discrete disconnection event that either occurs or doesn't (within a given probability) but instead there is a year-round average cost per hour at which the boundary must be constrained which implicitly includes the probability of a constraint existing. The constraint cost per hour is dependent upon the number of circuits unavailable by the asset failure, Y. In the vast majority of cases this will be 1, but tower failures would usually result in two circuits being lost until the asset can be restored. Additionally, the extra constraint cost that would result from unrelated unavailability on another circuit on the same boundary must be considered.

The derivation of average constraint costs will be based on flow and price information provided by the System Operator on an annual basis. The System Operator will run simulations of a full year of operation with each boundary in with intact, N-1 depletion, N-2 depletion and N-3 depletion capabilities resulting in four annual costs of operation for the boundary, B_Y, which is then calculated as follows:

Equation 131

$$B_1 = \frac{[(annual\ n-1\ cost) - (annual\ intact\ cost)]}{8760}$$

Equation 132

$$B_2 = \frac{[(annual\ n-2\ cost) - (annual\ intact\ cost)]}{8760}$$

Equation 133

$$B_3 = \frac{[(annual\ n-3\ cost) - (annual\ intact\ cost)]}{8760}$$

While a failure mode that renders Y circuits unavailable will incur costs at least the B_Y level, on average a proportion of the duration of the failure mode will be spent with Y+1 circuits unavailable, defined as P_{Y+1}. The

proportion used is derived from historic fault and outage probabilities and durations. The probability of sustained boundary depletion beyond Y+1 circuits is assumed to be negligible.

These costs are multiplied by the duration of the unavailability of the asset until it is returned to service, D_{fm}, dependent upon historic precedent for the asset type and failure mode in question.

With the variables defined the methodology for determining the boundary transfer risk cost, $R_{boundary}$, of an asset failure mode of any asset can be described by Equation 134.

Equation 134

$$R_{boundary} = D_{fm}[B_Y(1 - P_{Y+1}) + B_{Y+1}P_{Y+1}]$$

This methodology will return non-zero risk costs for all assets that belong to or affect circuits critical to the capability of one or more system boundaries with significant constraint implications.

Equation 134 can be illustrated with the example of B6, the boundary between the SPT and National Grid Electricity Transmission (NGET) areas. There are currently five circuits that make up this boundary. If a failure of an asset which makes up part of one of these circuits occurs then this circuit will be unavailable until the failure has been rectified, Y = 1 for this failure. The boundary will be at N-1 depletion until the failure is rectified and on average will spend some proportion, P_{Y+1}, of the duration of failure at a N-2 depletion level due to unrelated prior outages or other unrelated faults. The weighted average boundary constraint cost per hour is calculated by first multiplying B_1 by (1- P_{Y+1}), the proportion of time that the boundary is at N-1 depletion. Then B_2 is multiplied by the proportion of time that the boundary will spend at N-2 depletion, P_{Y+1}. These two products are added together. This average boundary cost per hour is then simply multiplied by the average time taken to restore the circuits to service by repairing the failed asset, D_{fm}. This gives us the total expected boundary constraint for the failure mode of the asset.

8.1.7.   REACTIVE COMPENSATION

The third methodology calculates the cost impact of having reactive compensation unavailable due to a fault or failure of any asset that would render the reactive compensation unusable. This could include circuit breakers, transformers and cables as well as the compensation itself. The purpose of reactive compensation is to produce or consume reactive power to aid control of system voltage. When compensation equipment is unavailable this reactive power control is either procured from generators instead or elements of the transmission system are de-energised, reducing system resilience. As a simplification, the cost impact of a fault or failure can be quantified as the volume of reactive power not supplied multiplied by the cost per MVArh the SO must pay to buy the same service from generators. Therefore, we have to calculate the reactive compensation system risk cost, RRC, of an asset Failure Mode:

Equation 135

$$R_{RC} = R_F D_{fm} Q C_{MVArh}$$

R_F is the requirement factor of the compensation equipment made unavailable or the proportion of the year that the compensation in question is required on a scale of 0 to 1. D_{fm} is the duration of unavailability due to

the asset failure mode. Q is the capacity of the asset in MVAr and C_{MVArh} is the average cost of procuring of MVAr from generation sources.

C_{MVArh} will be calculated by taking an annual sum of all costs of generators to absorb MVArs including BM actions to bring plant into service and constrain others as well as the cost of providing the reactive absorption itself. This sum is divided by the total number of MVArhs that were absorbed by generators over the year.

8.2.   SAFETY CONSEQUENCE

When assets fail, they have the potential to cause harm to both the public and personnel who work on or near to the assets. In circumstances where this does happen society there is an incurred cost. The aim of this part of the methodology is to therefore capture the safety risks that deteriorating assets present to individuals who are exposed to their effects and the associated cost. In general, the safety risk for an individual asset can be expressed as shown below:

Equation 136

$$Safety\ Risk = Probability\ of\ Failure\ Mode\ Effect\ \times\ Safety\ Cost$$

Where:

- **Probability of Failure Mode Effect** – represents the likelihood of different effects occurring because of assets failing

- **Safety Cost** – represents the safety related costs associated with asset failure

For an individual asset, the general expression for 'Safety Cost' is:

Equation 137

$$Safety\ Cost = Probability\ of\ Injury\ \times\ Cost\ of\ Injury\ \times\ Exposure$$

The terms in the expression hold the following meanings:

- **Probability of Injury** – the likelihood that an individual is injured when exposed to the effects of an asset failure

- **Cost of Injury** – the cost associated with an individual sustaining an injury

- **Exposure** – modifier to reflect the number of people who are exposed to the effects of an asset failure

Individuals exposed to asset failures can potentially sustain injuries of varying severity and the likelihood of these injuries occurring will depend on the asset under consideration, the type of failure that occurs and the effects associated with that failure. Moreover, the cost associated with different types of injury will vary. Considering these variables, the 'Safety Cost' can be more formally expressed as shown below:

Equation 138

$$Safety\ Cost_i = \sum_j Probability\ of\ Injury_{j,i} \times Cost\ of\ injury_j \times Exposure_j$$

Where:

i	=	Failure Mode Effect
j	=	Injury Type

The total 'Safety Risk' associated with the asset can therefore be expressed as shown in the below equation.

Equation 139

$$Safety\ Risk = \sum_i PoE_i \times Safety\ Cost_i$$

Where:

PoE	=	Probability of Failure Mode Effect

8.2.1.   FAILURE MODE EFFECT & PROBABILITY OF FAILURE MODE EFFECT

The failure mode effect represents the possible effects that TOs consider because of failure and the probability of failure mode effect represents its likelihood of occurrence. The effects that are considered by the TOs and the calculation of their likelihood is described in the Licensee Specific Appendices, please refer to "Values of K" to understand the different failure modes.

8.2.2.   INJURY TYPE & PROBABILITY OF INJURY

The 'Probability of Injury' represents the likelihood that an individual is injured when exposed to the effects of an asset failure. Probabilities will be assigned to each 'Injury Type' considered. The probability assigned to each category will vary depending on the failure mode that occurs and the effects that occur because of the failure mode effect materialising. For less disruptive failures there may be no impact from a safety perspective and the probability of injury will be zero. In addition, because it is assumed that the probability of injury applies to an individual, the sum of probabilities across all injury types categories for a failure effect is less than or equal to unity (i.e. an individual's injuries can only be classified under a single category of injury).

8.2.3.   COST OF INJURY

Fixed costs will be assigned to the different injury types recognised by the HSE as per their website.

Whilst the appraisal values reflect a broad range of cost categories, for simplicity of presentation the appraisal values can be divided into two main component costs:

- Human costs - representing a monetary estimate of the loss of quality of life, and loss of life in the case of fatal injuries
- Financial costs, which are the sum of the following:
    - Productivity costs including:
        - net lost income, considering of loss of output and earnings due to absence from work, and offsetting transfers from one party to another, e.g. benefits payments are a cost to Government, but an equal and opposite offsetting benefit to individuals
        - production costs, such as cost of recruitment and work reorganisation
    - The cost of Employer's Liability Compulsory Insurance, less compensation pay-outs to individuals
    - Health and rehabilitation costs, such as NHS costs
    - Administrative and legal costs, such as costs of administering benefits claims

Each of these factors is discussed in the proceeding sections. The Licensee Specific Appendix consists of a table relating to the cost of certain types of injuries and this information is utilised through-out the rest of the calculations.

The 'Cost of Injury' will be calculated as below:

Equation 140

$$Cost\ of\ Injury_j = \sum Cost\ of\ Injury \times Disproportion\ Factor$$

A disproportion factor recognising the high-risk nature of the Transmission Industry is applied. Such disproportion factors are described by the HSE guidance when identifying reasonably practicable costs of mitigation. This value is not mandated by the HSE but they state that they believe that "the greater the risk, the more should be spent in reducing it, and the greater the bias should be on the side of safety".

The disproportion factor is included in each Licensee Specific Appendix under "Injury and Probability of Failure".

8.2.4. EXPOSURE

Safety consequences are specific to individual assets and their physical location. Some assets will expose a greater number of people to their failure effects than others depending on the levels of activity near to the asset. The 'Probability of Injury' only considers whether an individual will be injured assuming they are exposed to the effects of an asset failure and does not consider whether it is likely that one or more individuals will be within the vicinity of an asset when it fails. To take into account the likely number of people exposed to the effects of an asset failure an 'Exposure' modifier is incorporated into the 'Safety Cost' calculation.

Equation 141

$$Exposure = Location\ Risk\ Rating\ \times\ Type\ Risk\ Rating$$

Under the Electricity Safety Quality and Continuity Regulations 2002 (ESQCR), risk assessments must be carried out on substation sites and overhead lines to assess the risk of interference, vandalism or unauthorised access to the asset by the public.

The Licensee Specific Appendix consists of 2 calibration tables which are used to describe the location risk and the type risk associate with exposure. Refer to "Exposure" section of the Licensee Specific Appendices for further information.

8.3. ENVIRONMENTAL CONSEQUENCE

When assets fail, they have the potential to impact on the geographical local area to the asset. The aim of this part of the methodology is to capture the environmental risks that deteriorating assets present to the environment and the associated cost. In general, the environmental risk for an individual asset can be expressed as shown below:

Equation 142

$$Environmental\ Risk_i = \sum_i (Probability\ of\ Failure\ Mode\ Effect\ \times\ Consequence\ of\ Environmental\ Impact)_{jk}$$

Where:

j	=	Probability of Failure Mode Effect
k	=	Consequence of Environmental Impact

- **Probability of Failure Mode Effect** – represents the likelihood of different effects occurring because of assets failing

- **Consequence of Environmental Impact** – represents the environment related costs associated with asset failure

8.3.1. FAILURE MODE EFFECT & PROBABILITY OF FAILURE MODE EFFECT

The 'Probability of Failure Mode Effect' represents the likelihood that an environmental impact occurs when an asset fails. Probabilities will be assigned to each 'Failure Mode' considered. The probability assigned to each category will vary depending on the failure mode that occurs and the effects that occur because of the failure mode effect materialising. For less disruptive failures there may be no impact from an environmental perspective, and the probability of environmental impact would be zero. In addition, because it is assumed that the probability of impact applies to an individual site, the sum of probabilities across all impact type categories for a failure effect is less than or equal to unity (i.e. the environmental impact that occurs at a site can only be classified under a single severity category).

The failure mode effect represents the possible effects that TOs consider because of failure and the probability of failure mode effect represents its likelihood of occurrence.

8.3.2.   CONSEQUENCE OF ENVIRONMENTAL IMPACT

The consequence of Environmental Impact will be made up of the factors below:

Equation 143

$$Consequence\ of\ Environmental\ Impact_i = \sum_i (Environmental\ Impact\ Costs\ \times\ Impact\ Volume\ \times\ Exposure)_{jk}$$

Where:

i	=	Environmental Impact Costs
k	=	Impact Volume
l	=	Exposure

- **Environmental Impact Costs** – Represents the average cost of each environmental impact

- **Impact Volume** – Represents the average volume of environmental impact per failure mode effect

- **Exposure –** Determined by the location and size of the asset

8.3.2.1.   ENVIRONMENTAL IMPACT TYPE & COSTS

Varying types of environmental damage can occur because of asset failure. The types of environmental impacts are categorised below:

Impact Type	Environmental Impact Measure
Oil	Average volume of oil lost per failure (litres)
SF6	Average volume of SF_6 lost per failure (kg)
Fire	Average probability that failure results in a fire
Waste	Average quantity of waste per failure (t)

Table 8

Details of the costs and calculations are specified in the Licensee Specific Appendices.

8.3.2.2.   IMPACT VOLUME

This value is specific to each TO and represents the average chance of a fire, as well as the average volume of oil, SF_6 and waste generated by each Failure Mode Effect per voltage per asset type.

8.3.2.3.   EXPOSURE

Due to the distributed nature of the transmission assets it is important that exposure is considered. Environmental consequences are specific to individual asset size and their physical location. Some assets pose a greater risk to the environment than others. To account for this, an 'Exposure' modifier is incorporated into the 'Environmental Cost' calculation;

Equation 144

$$Exposure = Proximity\ to\ Water\ Course\ Factor\ \times\ Asset\ Located\ within\ SSSI$$

8.3.2.3.1   PROXIMITY TO WATER COURSE FACTOR

This factor allows for an adjustment to be made based on an assessment of the based on the proximity of an asset to a water course. A calibration table with these values is included in the Licensee Specific Appendices.

The default value for Location Factor is 1. The default value shall be applied to all those Asset Categories that are not shown in the Licensee Specific Appendices.

8.3.2.3.2   ASSET LOCATED WITHIN SSSI

This section is used to indicate whether an asset is located within a Site of Special Scientific Interest and will apply a multiplying factor accordingly. This is due to the recognition that any environmental impact within an SSSI is likely to have a more devastating effect.

The default value for Location Factor is 1. The default value shall be applied to all those Asset Categories that are not shown in the Licensee Specific Appendices.

8.4.   FINANCIAL CONSEQUENCE

The Financial Cost of Failure is derived from an assessment of the typical replacement and repair costs incurred by the failure of the asset in each of its applicable Failure Modes and is multiplied by the probability of each Failure Mode

Equation 145

$$Financial\ Risk = \sum_i (Probability\ of\ Failure\ Mode\ Effect_i$$
$$\times\ Financial\ Consequence\ of\ Failure\ Mode\ Effect_i)$$

Where:

    i   =   Failure Mode Effect

- **Probability of Failure Mode Effect** – Represents the likelihood of different effects occurring as a result of assets failing

- **Financial Consequence of Failure Mode Effect** – Represents the financial costs associated with asset failure

8.4.1.   FINANCIAL CONSEQUENCE OF FAILURE MODE EFFECT

Equation 146

$$Financial\ Consequence\ of\ Failure\ Mode\ Effect$$
$$= \sum_i (Financial\ Consequence\ of\ Failure\ (£)_i\ \times\ Location\ Factor_i)$$

Where:

- **Financial Consequence of Failure (£)** – Represents the cost of asset repair/replacement

- **Location Factor** – Represents the financial impact of an assets location in the event of a repair or replacement

The Financial Consequence of Failure Mode Effect is the cost to return the asset to service (which may extend to full replacement of the asset). This is determined based on the failure modes of the relevant asset considered: -

- **Defect:** The costs associated with addressing a Defect Failure would not usually necessitate full asset replacement. Unless otherwise stated, a value equivalent to 5% of the Asset Replacement Costs has been adopted

- **Minor:** The costs associated with addressing a Minor Failure would not usually necessitate full asset replacement; however, the works would normally be over and above those associated with addressing a Defect Failure. Unless otherwise stated, a value equivalent to 15% of the Asset Replacement Costs has been adopted

- **Significant:** The costs associated with addressing a Significant Failure would not usually necessitate full asset replacement; however, the works would normally be over and above those associated with addressing a Minor Failure. Unless otherwise stated, a value equivalent to 40% of the Asset Replacement Costs has been adopted

- **Major:** A failure of this type would necessitate full asset replacement. Asset Replacement Costs have therefore been adopted, unless otherwise stated

8.4.2.   LOCATION FACTOR

The resulting Financial Cost of Failure value can then be modified for individual assets within a Lead Asset Category based on the application of a Location Factor to result in a Financial CoF that reflects the characteristics of an individual assets location.

Location Factors other than 1, may be applied to Assets that meet the "Non-Standard" Criteria, which is defined below:

- Major Crossings (e.g. railway lines, major road, waterways)

- Rural Locations & Islands (difficult to reach with machinery/support vehicles)

- Built up Location (City centres causing disruption)

- AONBs/NSA/NP (extra costs incurred due to scenic areas)

A calibration table for these location Factor values is included in the Licensee Specific Appendices under "Location Factor"

9. LONG-TERM MONETISED RISK BENEFIT

9.1. INTRODUCTION

The Long-term Monetised Risk Benefit (LTRB) is a relative measure of Monetised Risk reduction achieved through asset interventions and measured over a defined period of time enabling the TOs to estimate the benefits delivered by different types of interventions on a given asset.

The Long-term Monetised Risk Benefit is used by Ofgem to set outputs associated with TOs' asset management activities during the price control and enables the estimation of the consumer benefit of the proposed investment plans that can be used in a cost benefit analysis.

9.2. LONG-TERM RISK BENEFIT CALCULATION

The Long-term Monetised Risk Benefit is calculated as the risk reduction achieved by an asset or a group of assets when a certain intervention is applied as compared with the 'no intervention' scenario. This risk reduction is measured over the long-term using the forecasted risk value of the asset or group of assets into the future.

9.2.1. SURVIVAL MODEL

The LTRB calculation considers the concept of "survival risk" and therefore the Monetised Risk value associated with an asset is adjusted considering the probability of survival of that asset. In order to calculate the survival risk of an asset, an 'End of Life' probability of failure is required. The concept of 'End of Life' probability of failure corresponds to a failure mode that would result in a catastrophic failure of an asset that would leave the asset damaged to the extent that the only possible course of action would be the replacement of the asset. SPT-SSENT NARM Methodology does not include such failure mode, therefore Major Failure mode effect has been used as a proxy of the 'End of Life' probability of failure.

The Survival Risk of an asset in any given year Y, is calculated as follows in Equation 147

Equation 147

$$SR_Y = AR_Y \times (1 - PoF_{End\ of\ Life\ Y-1})$$

Where:

AR_Y is the Asset Risk of any given asset in year Y

PoF$_{\text{End of Life}}$ is the probability of 'End of Life' failure of any given asset, as a proxy PoF$_{\text{End of Life}}$ =PoF $_{\text{Major}}$ $_{\text{failure mode}}$

9.2.2. NOMINAL AND PRESENT VALUE LTRB

The nominal LTRB of an intervention is calculated by summing up the Survival Risk reduction achieved by that intervention in all the NARM assets impacted by the intervention as compared with the 'no intervention' scenario. This risk reduction is measured over a number of years into the future corresponding to the lifetime of the intervention. The lifetime of the intervention is the expected number of years until the asset reaches a condition requiring a further intervention. The nominal LTRB is calculated in Equation 148

Equation 148

$$LTRB_{Intervention\ A} = \sum_{Y0}^{Y_{lifetime\ intervention\ A}} (SR_{Y\ Intervention\ A} - SR_{Y\ No\ Intervention})$$

where:

SR$_{\text{Y Intervention A}}$ is the survival risk of the NARM assets impacted by intervention A

SR$_{\text{Y No intervention}}$ is the survival risk of NARM asset that would be impacted by intervention in the case of 'no intervention'

Y0 is the year of intervention A

A discount rate in applied to future values of Monetised Risk Benefit to derive the net present value at a specific moment in time, in this case the common reference used is the end of the price control. The Present Value LTRB is calculated by applying a discount rate corresponding to an annual rate of 3.5% in the first 30 years, reducing to 3% thereafter. The discount rates follow the recommend values in the HM Treasury Green Book Supplementary guidance[10].

9.2.3. LTRB IN COST BENEFIT ANALYSIS

The LTRB is a useful measure of consumer benefit in a cost benefit analysis and can be used to compare the efficiency of different asset interventions over a defined assessment period. For the purposes of the definition of the T2 price control, the chosen assessment period is 45 years therefore all cost and benefits associated with asset interventions over that period should be considered. As such it may be necessary to risk model more than one intervention over this time horizon. In most cases this involves the replacement of the asset after a refurbishment ceases to be effective.

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https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/193938/Green_Book_supplementary_guidance_intergenerational_wealth_transfers_and_social_discounting.pdf

10.   ASSET INTERVENTIONS

10.1.   TYPES OF INTERVENTIONS

Certain types of intervention will address failure modes. These may be routine interventions, such as maintenance, or specific, such as planned replacements.

The available interventions for managing the performance of assets range from routine maintenance to full replacement.

These activities are undertaken to ensure the longevity and performance of the TOs' networks. Without effective management of these activities, and understanding the related interactions between them, the TOs would, in time, experience deterioration of asset performance which would have a significant detrimental impact on the capability of the network.

Figure 27 Risk due to failure mode against time illustrates different types of intervention that would address failure modes in Table (not to scale).
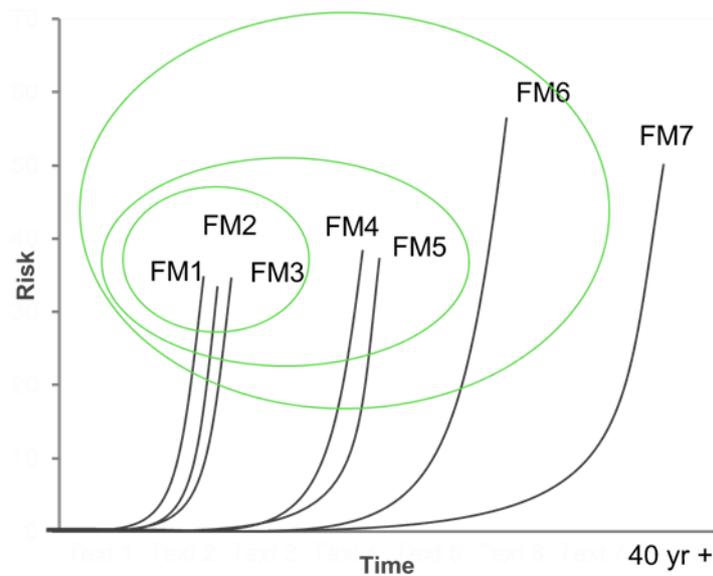
Figure 27 Risk due to failure mode against time

Failure Mode	1	2	3	4	5	6	7
Basic Maintenance	✔	✔	✔	✗	✗	✗	✗
Major Maintenance	✔	✔	✔	✔	✔	✗	✗
Repair	✔	✔	✔	✔	✔	✔	✗
Refurbishment	✔	✔	✔	✔	✔	✔	✗

| Replacement | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ |

Table 9

Several failure modes can happen within a similar time frame/ duty cycle, so the work to be carried out needs to be selected carefully to:

- Ensure that the relevant failure modes are adequately addressed
- Reduce the whole life cost
- Limit the impact of constraints such as outages and resources.

Interventions are determined by understanding how to prevent failure modes and the collection of data to predict failures. Knowing the asset's position on each failure mode curve enables the Transmission Owner to make a targeted intervention specifically addressing those failure modes most contributing to the risk. Following the intervention, the asset risk on the asset is reduced for that failure mode.

Asset replacements are taken into consideration by removing the Asset Risk of the existing asset and adding in the Asset Risk of the new asset. In contrast, the effect of repair and refurbishment activities are taken into consideration by revaluating the appropriate condition points once the intervention has been completed, refreshing the relevant data points and recalculating End of Life Modifiers to confirm the improved condition of the asset. These changes result in a reduced current and future End of Life Value, Probability of Failure and Asset Risk.

10.1.1.   MAINTENANCE

The purpose of asset maintenance is to achieve expected asset life and ensure asset performance, as well as allowing the TOs to gather condition information so that performance risks are better understood and mitigated.

Maintenance is a fundamental tool in the TOs' management of network reliability, safety and environmental performance (and hence customer satisfaction). Reducing maintenance to zero, or reducing levels without undertaking impact assessments, would lead to a decline in the condition of assets (this effect is seen more rapidly than for under-investment in replacement), leading to increased unplanned events and in some cases bringing forward the need for asset replacement or increasing refurbishment activities.

Maintenance policy evolves as processes and practice are periodically reviewed. The TOs reassess maintenance policy and interval decisions on an ongoing basis using the latest information available to ensure assets can achieve their anticipated asset lives and reduce the potential for unplanned disruption. Maintenance activity can uncover developing trends for defects, ensure rectification of unforeseen functional failure modes and can enable innovation.

When developing maintenance content and undertaking frequency reviews, the TOs have a systematic, structured method for cost/benefit evaluation. This includes understanding the asset's reliability for known failure modes, taking account of how the operating costs would be expected to increase during the time between maintenance tasks, identifying potential changes in performance and consideration of the impact that a change to the maintenance task frequency might have on the life of the asset. As part of the planning process, maintenance is bundled into efficient packages to optimise access to the network and the assets.

Through maintenance activities the TOs can manage the natural deterioration of asset condition so that the assets remain operable throughout their anticipated technical life, reducing unplanned outages on the network as well as monitoring the condition of assets to improve understand of their performance. This then feeds into future asset intervention plans.

Maintenance activities are pro-active interventions which take place at regular intervals per policy. Undertaking maintenance activities ensures that the assets function correctly and can identify issues with the assets which can be addressed prior to a failure mode occurring.

A basic maintenance will involve basic checks for function of components as well as activities such as visual inspections, checks for fluid/gas levels where appropriate.

An intermediate maintenance takes place at longer intervals than a basic and will include all activities undertaken for a basic maintenance but will include additional checks on specific components of the equipment.

A major maintenance will include all the activities undertaken for a basic and intermediate maintenance but will also include comprehensive and possibly intrusive work as well as more exhaustive checks. These take place less regularly than basic and intermediate levels and generally require a significantly longer outage to carry out the work.

The intervals for the maintenance activities are determined through maintenance policy for each asset type, per the specific requirements for that asset and manufacturer data recommendations are also considered.

10.1.2. REPAIR

Repair is a reactive activity responding to a failure mode when it has occurred. In some cases, it can prevent another failure mode. Repair activities should allow the lead assets to achieve expected life and ensure asset performance. For some failure modes, which cannot be detected on a routine basis such as by maintenance or inspection, repair is the only available intervention once the failure mode has occurred. That is not to say that detection of the failure mode is not available and assets are monitored for known failure modes. For example, cable oil pressure is monitored and an alarm triggered if the pressure falls below a certain level. The failure mode is detected as the oil leak initiates but there are no routine interventions available to detect the occurrence of a leak before it occurs.

The only available option is to repair the cable when the oil leak is detected. Some failure modes, which lead to another failure mode, can be detected prior to failure, for example, sheath testing of cables will reveal defects in the over-sheath which, if left unrepaired, will eventually lead to the corrosion of the sheath and subsequently an oil leak. A repair intervention can then be planned to mitigate this risk.

10.1.3. REFURBISHMENT

Refurbishment is a planned one-off activity on an asset that is deemed to be close to end of life or is otherwise requiring intervention that extends the life of the asset. Refurbishment can include the replacement or reconditioning of components of an asset.

The ongoing lifetime cost of supporting a refurbished asset family must also be considered. It may be more cost-effective to replace highly complex units that require frequent intervention.

Continuing spares support must be considered. Whilst some spares can be re-engineered without significant risk, this is not appropriate for performance critical components. If such components are unavailable (or not available cost-effectively), refurbishment is unlikely to be a realistic option.

Additionally, the condition and deterioration mechanisms of the asset class must be well understood. If these criteria are met, and it is considered that refurbishment is a viable option, it would be expected that refurbishment activities would change the asset's condition and/or extend asset life.

10.1.4.   REPLACEMENT

Individual assets or families which are deemed to be a priority given their risk trigger the need for replacement and capital investment. There may also be instances where the frequency of repair (and associated cost) is such that replacement is considered economic. To facilitate the development of an optimised replacement plan, priority ranked lists for replacement are created for each asset type.

10.1.5.   HIGH IMPACT, LOW PROBABILITY EVENTS

A significant amount of work has been undertaken by the TOs with respect to High Impact, Low Probability events. However, given the difficulties involved in quantifying Risk in this area, it has been agreed that these events shall not undergo separate treatment within this methodology. The onus is on the individual TO and the business's risk appetite to determine how these events should be managed.

11. LEAD ASSETS DETERIORATION MECHANISMS

The following sections provide background and high level deterioration mechanisms for the lead assets.

11.1. CIRCUIT BREAKERS

11.1.1. BACKGROUND

Circuit breakers are different to other lead assets as they generally have limited condition information on an individual asset basis. To gather additional condition information on sub components which has the potential to affect the end of life modifier, would require invasive work to assess the actual condition of a sub component. It is undesirable to do so in most situations as this invasive assessment carries a significant potential to adversely affect the asset's health.

Technically effective or cost justified diagnostic techniques, including continuous monitoring, are limited for use on large populations and are not applicable for deterioration modes determining the end of life of most types of existing circuit breaker. In addition, the deterioration age range is related to the equipment's environment, electrical and mechanical duty, maintenance regime and application.

In this methodology, a family specific deterioration component to the end of life modifier formula is introduced to account for missing condition information. Assignment to family groupings is through identification of similar life limiting factors. Family groupings are broadly split into interrupter mechanism type.

Known deterioration modes have been determined by carrying out forensic analysis of materials and components during replacement, refurbishment, maintenance and failure investigation activities or following failures. The output of the forensic analysis reports has been used to both inform and update the relevant deterioration models. Anticipated technical asset lives are based on the accumulated engineering knowledge of TO's defect, failure statistics and manufacturer information. The method for mapping this knowledge to the end of life curve was presented in the functional modes and affects analysis section.

11.1.2. DETERIORATION

Circuit breakers are made up of several sub-components. These sub-components deteriorate at different rates, are different in relation to their criticality to the circuit breaker function and finally have different options regarding intervention

Although there is a correlation between age and condition, it has been observed that there is a very wide range of deterioration rates for individual units. The effect of this is to increase the range of circuit breaker condition with age, some circuit breakers becoming unreliable before the anticipated life and some showing very little deterioration well after that time.

11.1.3. AIR-BLAST CIRCUIT BREAKER TECHNOLOGY

As Air-Blast Circuit Breaker (ABCB) families approach their end of life an assessment is made regarding the relative economic impact of replacement or refurbishment considering factors such as technological complexity, population size and ongoing asset management capability for the design. Since most ABCB families are no longer supported by their original equipment manufacturer, the cost and feasibility of providing parts, skilled labour and ongoing technical support makes asset refurbishment unfeasible.

Using the above approach refurbishment has, in selected cases, proven to be an effective way to extend the Anticipated Asset Life (AAL) for Conventional Air-Blast (CAB) and Pressurised head (PAB) ABCBs.

The replacement of ABCBs is considered alongside the remaining lifetime of the associated site air system. If removal of the last ABCBs at a site allows the site air system to be decommissioned, early switchgear replacement may be cost beneficial when weighed against further expenditure for air system replacement and/or on-going maintenance.

11.1.4. OIL CIRCUIT BREAKER TECHNOLOGY

There are a number of life limiting factors that impact oil circuit breakers. These include degradation of the bushings, reduction in contact compression and associated failure, stress cracks in support structures and multiple mechanism issues. The available support from the original equipment manufacturer, cost and feasibility of providing parts, and availability of skilled labour makes asset refurbishment unfeasible.

11.1.5. SF$_6$ GAS CIRCUIT BREAKER TECHNOLOGY

The bulk of the Gas Circuit Breaker population (GCB) have not yet required replacement. A similar process to that followed for the ABCB families is being undertaken to identify refurbishment (i.e. life extension) opportunities. Where this is not technically-feasible or cost-effective, replacement is planned.

The GCB population includes many small families, with variants and differing operating regimes, and so the identification of large-scale refurbishment strategies may not be cost-effective. Technical and economic evaluation as well as further development of refurbishment strategies will take place.

Non-SF$_6$ alternative gas technologies are becoming available and although current use is very limited, the volume of circuit breakers using alternative gases will be increasing in the coming years. The deterioration mechanisms for these new circuit breakers in still unknown and development of a suitable risk model should form part of future developments of this methodology.

The SF$_6$ circuit-breakers which are installed on shunt reactive compensation could be subject to very high numbers of operations (typically several hundred per year). The "end of life" of these circuit-breakers is likely to be defined by exceeding the circuit breakers' mechanical endurance limits rather than age related deterioration. It is likely that if refurbishment of these circuit breakers was considered then full mechanism and interrupters would require to be replaced. A cost benefit analysis should be undertaken to evaluate refurbishment or replacement. It is anticipated most types of high duty reactive switching circuit breaker would reach end of asset life based on the number of operations they have performed therefore development of a suitable calibration for this circuit breakers may be required in future reviews of this methodology.

11.2. TRANSFORMERS AND REACTORS

11.2.1. BACKGROUND

Transformers and reactors share similar end of life mechanisms since they are both based on similar technologies. The same scoring method is therefore applied to calculate the End of Life modifier. For simplicity within this section the term transformer is used to mean both transformer and reactor.

Transformers are assigned an end of life modifier per the condition inferred from diagnostic results, the service history, and post mortem analysis of other similar transformers.

The health of the overall transformer population is monitored to ensure that replacement/refurbishment volumes are sufficient to maintain sustainable levels of reliability performance, to manage site operational issues associated with safety risks and to maintain or improve environmental performance in terms of oil leakage.

The process by which transformers are assigned an end of life modifier relies firstly on service history and failure rates specific to designs of transformers and secondly on routine test results such as those obtained from Dissolved Gas Analysis (DGA) of oil samples. When either of these considerations gives rise to concern, then where practicable, special condition assessment tests (which usually require an outage) are performed to determine the appropriate end of life modifier. Special condition assessment may include the fitting of a continuous monitoring system and the analysis of the data to determine the nature of the fault and the deterioration rate.

The elements to be considered when assigning an end of life modifier are:

1. Results of routine condition testing
2. Results of special condition assessment tests
3. Service experience of transformers of the same design, and forensic examination of decommissioned transformers
4. Results of continuous monitoring where available

The following additional condition indications shall be considered when deciding the repair/replacement/refurbishment strategy for a transformer:

1. Condition of oil
2. Condition of the tap-changer
3. Condition of bushings
4. Condition of coolers
5. Rate of oil loss due to leaks
6. Condition of other ancillary parts and control equipment
7. Availability of spare parts particularly for tap-changers

11.2.2. TRANSFORMER AND REACTOR DETERIORATION

Thermal ageing of paper is the principal life limiting mechanism for transformers which will increase the failure rate with age. This failure mechanism is very dependent on design and evidence from scrapped transformers indicates a very wide range of deterioration rates. Knowledge of the thermal ageing mechanism, other ageing mechanisms and the wide range of deterioration rates are used to define the technical asset lives for transformers.

In addition to the above fundamental limit on transformer service life, experience has shown that several transformer design groups have inherent design weaknesses which reduce useful service life

The condition of Transformers can be monitored through routine analysis of dissolved gases in oil, moisture and furfural content together with routine maintenance checks. Where individual test results, trends in test results or family history give cause for concern, specialist diagnostics are scheduled as part of a detailed condition assessment. Where appropriate, continuous monitoring will also be used to determine or manage the condition of the transformer.

Methods exist to condition assess transformers and indicate deterioration before failure, however the time between the first indications of deterioration and the transformer reaching a state requiring replacement is varied and can depend on factors such as the failure mechanism, the accuracy of the detection method, and the relationship between system stress and failure. For this reason, the transformer models periodically require updating (supported by evidence from forensic analysis) as further understanding of deterioration mechanisms is acquired during the transformer life cycle.

11.2.3.   INSULATING PAPER AGEING

The thermal ageing of paper insulation is the primary life-limiting process affecting transformers and reactors. The paper becomes brittle, and susceptible to mechanical failure from any kind of shock or disturbance. Ultimately the paper will also carbonise and cause turn to turn failure, both mechanisms leading to dielectric failure of the transformer. The rate of ageing is mainly dependent upon the temperature and moisture content of the insulation. Ageing rates can be increased significantly if the insulating oil can deteriorate to the point where it becomes acidic.

The thermal ageing of paper insulation is a chemical process that liberates water. Any atmospheric moisture that enters the transformer during its operation and maintenance will also tend to become trapped in the paper insulation. Increased moisture levels may cause dielectric failures directly or indirectly due to formation of gas bubbles during overload conditions.

The paper and pressboard used in the construction of the transformer may shrink with age which can lead to the windings becoming slack. This compromises the ability of the transformer windings to withstand the electromagnetic forces generated by through fault currents. Transformer mechanical strength may be compromised if it has experienced several high currents through faults during its lifetime and the internal supporting structure has been damaged or become loose.

End of life because of thermal ageing will normally be supported by evidence from one or more of the following categories:

1. Forensic evidence (including degree of polymerisation test results) from units of similar design and load history
2. High and rising furfural levels in the oil
3. High moisture content within the paper insulation
4. Evidence of slack or displaced windings (frequency response tests or dissolved gas results)

11.2.4.   CORE INSULATION

Deterioration of core bolt and core-to-frame insulation can result in undesirable induced currents flowing in the core bolts and core steel under certain load conditions. This results in localised overheating and risk of Buchholz alarm/trip or transformer failure as free gas is generated from the localised fault. It is not normally possible to repair this type of fault without returning the transformer to the factory. Evidence of this end of life condition would normally be supported by dissolved gas results together with forensic evidence from decommissioned transformers of similar design. Insertion of a resistor into the core earth circuit can reduce or eliminate the induced current for a period.

11.2.5.   THERMAL FAULT

Transformers can develop localised over-heating faults associated with the main winding because of poor joints within winding conductors, poor oil-flow or degradation of the insulation system resulting in restrictions to oil flow. This is potentially a very severe fault condition. There is not normally a repair for this type of fault other than returning the transformer to the factory. Evidence of this end of life condition would normally be supported by dissolved gas results together with forensic evidence from decommissioned transformers of similar design.

11.2.6.   WINDING MOVEMENT

Transformer windings may move because of vibration associated with normal operation or, more commonly, because of the extreme forces within the winding during through fault conditions. The likelihood of winding movement is increased with aged insulation as outlined above. Where evidence of winding movement exists, the ability of the transformer to resist subsequent through faults is questionable and therefore the unit must be assumed not to have the strength and capability to withstand design duty and replacement is warranted. There is no on-site repair option available for this condition. Winding movement can be detected using frequency response test techniques and susceptibility to winding movement is determined through failure evidence and evidence of slack windings through dissolved gas results.

11.2.7.   DIELECTRIC FAULT

In some circumstances transformers develop dielectric faults, where the insulation degrades giving concern over the ability of the transformer to withstand normal operating voltages or transient overvoltage. Where an internal dielectric fault is considered to affect the main winding insulation, irreparable damage is likely to ensue. This type of condition can be expected to worsen with time. High moisture levels may heighten the risk of failure. Evidence of a dielectric problem will generally be based on operational history and forensic investigations from units of similar design, supported by dissolved gas results. Various techniques are available to assist with the location of such faults, including partial discharge location techniques. If evidence of an existing insulation fault exists and location techniques cannot determine that it is benign, then it should be considered that the transformer is at risk of failure.

11.2.8.   CORROSIVE OIL

In certain cases, high operating temperatures combined with oil containing corrosive compounds can lead to deposition of copper sulphide in the paper insulation, which can in turn lead to dielectric failure. This phenomenon may be controlled by the addition of metal passivator to the oil, however experience with this technique is limited and so a cautious approach to oil passivation has been adopted. Regeneration or replacement of the transformer oil may be considered for critical transformers or where passivator content is consumed quickly due to higher operating temperatures.

11.3.   UNDERGROUND CABLES

11.3.1.   BACKGROUND

Cable system replacements are programmed so that elements of the cable systems are replaced when the safety, operational or environmental risks of continued operation meet defined criteria.

Replacement of cable systems are based on several metrics including age. These metrics only include a few condition related components since there is limited information that can be obtained on how deteriorated a cable is. Further condition information could be obtained by digging up and taking samples of a cable, but this is not practical, would be costly and could also cause further failures.

The factors to be considered when determining an end of life modifier are:

1. Historical environmental performance
2. Historical unreliability
3. Risk of tape corrosion or sheath failure
4. Results of condition assessment and other forensic evidence
5. Service experience of cable systems of similar design
6. Number of defect repairs
7. Number of cable faults
8. Duty in terms of how much time annually a cable is running at or above its designed rating
9. Bespoke nature and issues associated with specific cable systems

11.3.2. DETERIORATION

End of technical life will generally be due to the deterioration of the main cable system; this may be associated with either mechanical or electrical integrity or withstand capability.

With the exception of cables vulnerable to reinforcing tape corrosion and cables where a known manufacturing defect has occurred (e.g. lead sheath deterioration), cable systems have generally given reliable operation and there is limited experience of long term deterioration mechanisms.

Cables can be split broadly into two classes for the purposes of understanding the end of life of this asset class, these are fluid filled cables and solid dielectric cables. In general, the cable circuit will only meet the criteria for replacement where refurbishment as described above will not address condition and performance issues and guarantee compliance with statutory requirements.

11.3.3. END OF LIFE MECHANISMS AFFECTING BOTH TYPES OF CABLES

11.3.3.1. LEAD AND ALUMINIUM SHEATH DETERIORATION

Fatigue and inter-crystalline cracking, and defects introduced during manufacture can cause oil leaks to develop. It is not generally possible to predict when a given cable section will fail because of this failure mode. Local repairs are not generally effective as sheath deterioration is usually distributed along the cable. End-of-life is reached where sheath deterioration is resulting in significant and widespread oil-loss (relative to duties in respect of recognised code of practice) along the cable length.

11.3.3.2. BONDING SYSTEM

Water ingress to link boxes causes deterioration of cross-bonding systems and leaves the link box and its Sheath Voltage Limiters (SVLs) vulnerable to explosive failure under fault conditions. Specific evidence shall be gathered through condition assessment to support end-of-life determination. This issue will in general be addressed by replacement of specific components during circuit refurbishment activity or enhanced routine maintenance.

11.3.3.3. COOLING SYSTEM

The life of a cable's cooling system is much shorter than the lifetime of the overall cable asset. Therefore, mid-life intervention maybe required to replace the cable cooling system components. While this is not the end of the life of the cable it is an important consideration as the cable is not able to do what, it was designed to do with a failed cooling system. Cooling systems tend to be unique to each cable route. Loss of the cooling capacity can typically reduce circuit rating by 40%. Most problems are experienced with the original control systems which are now obsolete. Aluminium cooling pipes are vulnerable to corrosion and plastic pipes are vulnerable to splitting, which can result in water leaks. Cooling control system and pumping equipment will also require replacement prior to the main cable system in line with circuit specific assessment. In general cooling pipework, should be managed through maintenance to achieve the asset life of the main cable system.

11.3.4. FLUID FILLED CABLE END OF LIFE MECHANISMS

11.3.4.1. REINFORCING TAPE CORROSION

Reinforcing tapes are used to retain the oil pressure for cables with lead sheaths. Corrosion of the tapes in certain early BICC cables and AEI cables results in the tapes breaking, the sheath splitting and consequential oil leaks. Methods are being developed for predicting failure using corrosion rates determined through sampling in combination with known operating pressures, and using degradation mechanism models. Local repairs are not considered effective mitigation as corrosion is usually distributed along the cable. End-of-life of the cable system is in advance of widespread predicted tape failure. The lead times for cable replacement schemes are considerably greater than the time to deteriorate from broadly acceptable to unacceptable cable system performance for this failure mode. This implies that pre-emptive action is required to minimise the likelihood of failure occurring. Acceptable performance is where the cable can be repaired on an ad-hoc basis; unacceptable performance is where the corrosion is distributed along a significant number of sections of the route.

11.3.4.2. STOP JOINT DETERIORATION

Stop-joint failure presents significant safety, reliability and environmental risk. End-of-life for stop joints will be justified based upon oil-analysis data or forensic evidence from similar designs removed from service. Stop joint deterioration can be addressed via refurbishment and would not alone drive replacement of the cable system.

11.3.4.3. CABLE JOINT DETERIORATION

In general, cable joint deterioration can be addressed via refurbishment and would not alone drive replacement of the joint or cable system.

11.3.4.4. OIL-ANCILLARIES

Corrosion of oil tanks, pipework and connections, and pressure gauges can result in oil leaks and incorrect operation of the ancillaries. Specific evidence shall be gathered through condition assessment to support end-of-life determination. This issue will in general be addressed by replacement of specific components during circuit refurbishment activity or enhanced routine maintenance.

11.3.4.5. ENVIRONMENTAL CONSIDERATIONS

TOs have a statutory obligation to comply with the Water Resources Act 1991/Water Resources (Scotland) Act 2013 and to fulfil their commitments with respect to its Environmental Statement. Utilities demonstrate compliance with the requirement of the Act through adherence to the guidance provided.

A factor to consider in determining end of technical life is when it is no longer reasonably practicable to comply with the requirements of the above legislation and guidance, and maintain a sustainable level of circuit availability.

11.3.4.6.   SOLID XLPE FILLED CABLE END OF LIFE MECHANISMS:

These cables have been installed at 132kV and 275kV for some years. There is limited service experience at 400kV. Provided high standards of manufacture and installation are available, the risk of early-life failures will be avoided. No end of life mechanism has yet been identified. The long-term deterioration mechanisms would benefit from further research and development.

11.4.   OVERHEAD LINES

11.4.1.   GENERAL APPROACH

Routes are fully refurbished, or have critical components replaced, to maintain reliability (including a level of resilience to extreme weather conditions), operational risk and safety performance. In addition, conductors should retain sufficient residual mechanical strength to facilitate safe replacement by tension stringing methods at end of life.

Technical asset lives for OHL components in various environments have been predicted using historical condition information from previous OHL replacement schemes, condition samples taken on existing assets, and an understanding of deterioration mechanisms.

Scoring assessments are made on sections of circuit that are typically homogenous in conductor type, installation date and environment.

11.4.2.   DETERIORATION

11.4.2.1. CONDUCTORS

Conductor end of life condition is a state where the conductor no longer has the mechanical strength (both tensile and ductility) required to support the combination of induced static and environmental loads.

Two main deterioration mechanisms exist:

1. Corrosion, primary cause pollution either saline or industrial
2. Wind induced fatigue, common types
    a. Aeolian vibration (low amplitude high frequency oscillation 5 to 150 Hz)
    b. sub-conductor oscillation (bundles conductors only) produced by forces from the shielding effect of windward sub-conductors on their leeward counterparts
    c. galloping (high-amplitude, low-frequency oscillation)
    d. wind sway

Conductor fatigue is usually found at clamp positions where the clamp allows more inter-strand motion within the conductor, leading to fretting of the internal layers. Loss of strand cross-section follows, then fatigue cracking, and finally strand breakage. This form of degradation is generally the life-limiting factor for quad bundles, clamping positions on twin bundles can also be affected.

Conductor corrosion is also usually found at clamp positions. Interwoven conductor strands open at these points allowing for easier ingress of corroding chlorides, sulphates and moisture etc. The zinc galvanising of the core wires is corroded, eventually exposing the underlying steel. A galvanic corrosion cell is then created where the aluminium wire is sacrificial. The loss of cross-section of aluminium leads to greater heat transfer to the steel core increasing the risk of core failure. Additionally, some spacer clamps with elastomer bushings that contain carbon and have a low resistance also lead to galvanic corrosion of aluminium strands, reducing thickness, strength and ductility.

In addition, end of life may be advanced, in rare instances, due to an unexpected load or events such as extreme wind ice or heat which overload (stress) the conductor beyond its design capability. Quality of the original manufacturing could also be an issue (galvanising defects). Insulators

The end of life occurs when the increased risk of flashover (loss of dielectric strength) reaches an unacceptable level due to condition, which may or may not result in mechanical failure of the string, or a decrease in mechanical strength due to corrosion of the steel pin.

11.4.2.2. FITTINGS - SPACERS, SPACER DAMPERS AND VIBRATION DAMPERS

The functional end of life of spacers, spacer dampers and vibration dampers occurs at the point at which the conductor system is no longer protected, and conductor damage starts to occur.

These items are utilised to protect the conductor system from damage. The main deterioration mechanism is wear or fatigue induced through conductor motion. Corrosion in polluted environments can also be an issue particularly inside clamps

Wear damage to trunnions and straps of suspension clamps occurs due to conductor movement. The wear has been greatest in areas of constant wind, i.e. higher ground, flat open land and near coasts. For quad lines, at wind exposed sites, wear can be extensive and rapid failures of straps, links, shackles and ball-ended eye links can occur. This is one of the best indicators of line sections subject to sustained levels of wind induced oscillation and hence where future conductor damage is likely to become a problem.

Most conductor joints for ACSR have been of the compression type, although bolted joints are used in jumpers. Overheating joints can arise from inadequate compression along the length of the joint, mainly due to either poor design or installation problems. These allow moisture penetration and oxidation of the internal aluminium surfaces between the joint and conductor. The resistive aluminium oxide reduces the paths for current flow and may cause micro-arcing within the joint. The consequence of this deterioration is that the joint becomes warm which further increases the rate of oxidation. Over a period, the resistive paths can result in excess current flowing in the steel core of the conductor, which can then overheat and rupture.

11.4.2.3. SEMI-FLEXIBLE SPACERS

These are fitted in the span and the semi-flexibility comes from either elastomer liners, hinges or stranded steel wire depending on the manufacturer. End of life is defined by perishing of the elastomer lining or broken/loose spacer arms. These allow for excessive movement of the conductor within the clamp leading to severe conductor damage in small periods of time (days to months, depending on the environmental input). The elastomer lining

of the Andre spacer type also causes corrosion of conductor aluminium wires due to its carbon content and subsequent galvanic corrosion. A common finding of conductor samples at these positions is strands with significantly poorer tensile and torsional test results. This is a hidden condition state unless it manifests in broken conductor strands that are visible on inspection.

Replacement of these spacers has been necessary on routes that are heavily wind exposed at approximately 25 years. There are many examples still in service beyond their anticipated life of 40 years where visual end of life characteristics have not yet been met. As the condition of the associated conductor within or near the clamp can remain hidden, certain families of this type of spacer such as the 'Andre' are identified for the increased risk they pose to conductor health.

11.4.2.4.   SPACER DAMPERS

As the service history of spacer dampers is limited, extensive data on their long-term performance and end of life is not yet available. The spacer arms are mounted in the spacer body and held by elastomer bushes. This increased flexibility should provide the associated conductor system with more damping and greater resilience to wind induced energy. End of life criteria will be defined by broken/loose spacer arms that allow for excessive movement of the conductor/clamp interface.

11.4.2.5.   VIBRATION DAMPERS

Stockbridge dampers have always been used for the control of Aeolian vibration, a minimum of one damper being installed at each end of every span on each sub-conductor. For long spans (where specified by the manufacture) two or more may be used. End of life is defined by loss of damping capability which is visually assessed in the amount of 'droop' in and wear of the messenger cable between damper bells. The useful life of a damper is constrained by wind energy input and corrosion of the messenger wire connection with the damper bells. In areas of high wind exposure there is evidence that dampers have required replacement after 10 to 15 years. There are however many more examples of dampers operating beyond their anticipated life with no visual signs of end of life.

11.4.2.6.   TOWERS

Corrosion and environmental stress are life-limiting factors for towers. The end of life of a whole tower is the point at which so many bars require changing that it is more economical to replace the whole tower. Degradation of foundations is another life-limiting factor for towers.

12. CONDITION ASSESSMENT METHODOLOGIES

As responsible Network Owners and Asset Managers, we continually monitor the condition and performance of our assets to ensure we provide the safe and secure network expected by our customers and stakeholders.

We treat asset condition as the primary driver for intervention. Within our asset management system, we generally categorise each of the condition points recorded for our assets on a 1-5 scale for SPT and 1-4 scale for SSENT. The scale indicates the observed condition and varies from 1 meaning good condition 'as new' to 4 or 5 to be indicative of 'end of life' condition.

The condition assessments are carried out on periodic basis, appropriate for the specific asset type. Qualitative and quantitative assessment is undertaken in accordance with established TO specific policy, taking into account industry best practise on both timing and the techniques used.

Detailed network and asset knowledge is essential in the application of the NARM methodology therefore the condition assessment methodologies and asset data systems have evolved in recent years to ensure better and more detailed data availability and consistency.

12.1. SUBSTATION ASSET DATA COLLECTION

The data collection of the observed condition is undertaken by experienced operational staff using standardised question sets which capture the NARM methodology requirements. The data returns are then reviewed by experienced engineers to ensure consistency before the data is recorded in the systems. The condition assessments cover all lead assets in the substation such as circuit breakers, transformers and reactors and non-lead assets such as AC/DC supplies, compressors, air systems and civil assets. The non-lead assets do not form part of the NARM methodology however we assess its condition in a similar fashion to determine any intervention requirements on those.

The measured condition focus on oil and gas condition for circuit breakers, transformers and reactors. We also use Dissolved Gas Analysis techniques for transformers and reactors.

12.2. OVERHEAD LINE ASSET DATA COLLECTION

The data collection for observed condition in Overhead Lines is done through aerial inspections either by helicopter or drones, walking and tower climbing inspections.

The measured condition focus on conductor non-intrusive testing such as Cormon test, mid-span or jumper sampling forensic analysis and foundation intrusive inspections.

12.3. UNDERGROUND CABLE ASSET DATA COLLECTION

The data collection for the observed condition in underground cables is limited to hydraulic and earthing systems since most cables are buried.

The measured condition focus on partial discharge monitoring, sheath and SVL testing to the critical accessories to the cable system.

13. INNOVATION AND FORWARD-LOOKING METHODOLOGY DEVELOPMENTS

Part C of Special Condition 9.2 requires that each licensee must, at least once every year, review the NARM Methodology. The objective of this review is that of continuous improvement, and better facilitating the achievement of NARM Objectives.

As part of the NARM Methodology Review the following areas have been identified as category two actions for the continuous improvement of the NARM methodology. These are priority areas to develop in preparation for the next price control period:

- System consequences calibration. These values need to be updated to reflect the changes in prices since these values were originally set. Based on the experience of using the Methodology it has been identified that the Duration values need to be analysed and reviewed. The calibration of the cost of generation compared with cost demand also needs to be reviewed.
- Financial COF values update. In order to allow these values to be published in the LSA the use of benchmark financial consequence values, based on standard values agreed between TOs, is to be considered.
- Long term risk benefit calculation review. The different methodologies used in the ETO sector need to be reviewed to improve alignment and a greater alignment within the ET sector considered.
- Development the stakeholder engagement strategy concerning NARM.
- Steel tower risk model review to identify improvement opportunities in the modelling of the steelwork and protective coating, longer term.
- Initiate further analysis works to harmonize probabilities of failure for the different assets/components across Electricity Sector, longer term.

Digitisation and Innovation present opportunities to improve the NARM methodology, the following areas have been identified as potential areas to explore in the future:

During the RIIO-T2 Price Control on-line monitoring capabilities, for example Dissolved Gas Analysis, SF6 Gas Density Monitoring and Partial Discharge Monitoring, are being installed on certain assets. It is envisaged this will allow for updating condition of assets in "near real time".

Further methodology development, when this condition information becomes available, will allow for the combination of "static" inputs currently available with "near real time" inputs collected from on-line monitoring and will generate a more accurate End of Life score as more relevant and the most current inputs will be considered in quantifying assets' condition.

The NARM Methodology currently calculates Asset Risk for lead assets only, future development of the methodology could consider widening the scope to include additional asset types. For example earth switches, disconnectors, CT and VTs.

14. GLOSSARY OF TERMS

Asset Risk	The sum of the expected values of each consequence associated with an asset and a function of the probability of each failure mode effect associated with that asset.
Asset Class	A group of assets with similar characteristics
Asset Management	Coordinated activity of an organisation to realise value from assets
Consequence	Outcome of an event affecting objectives*
Conditional Factors	Factors that lead to an assets failure due to its physical condition
Consequence of Failure	A consequence can be caused by more than one Failure Mode. This is monetised values for the Safety, Environmental, System and Financial consequences
Cost of Consequence	The costs incurred due to a consequence of failure manifesting across a site.
Deterioration	Progressive worsening of condition
the Direction	Ofgem Direction document from April 2016
EoL Modifier	End of Life number that modifies or is modified to produce an End of life value
EoL Value	The target EoL value used for Modifies or is Modified to produce an End of Life value.
Event	Occurrence or change of a particular set of circumstances*
Failure	A component no longer does what it is designed to do. May or may not result in a fault
Failure Mode	A distinct way in which a component can fail
Fault	An asset no longer functions and intervention is required before it can be returned to service
Intervention	An activity (maintenance, refurbishment, repair or replacement) that is carried out on an asset to address one or more failure modes
Level of risk	Magnitude of a risk or combination of risks, expressed in terms of the combination of consequences and their likelihood*
Licensee(s)	One or more of the TOs
Likelihood	Chance of something happening*
Load Related	Works on a transmission system required due to an increase in demand and/or generation
Modified Anticipated Life	The anticipated life value gathered from manufacturer data that is modified with respect to how much the asset is doing and where it is located.
Maximum Multiple Increment technique	Combines multiple factors together to produce a single overall factor with respect to the components factors various weightings of importance
Monetised Risk	An estimation of Asset Risk as derived in accordance with the NARM Methodology as well as the similarly derived estimated risks associated with aggregated asset groupings, and disaggregated sub-components, as relevant.
Network Risk	The sum of all the Asset Risk associated with assets on a TO network
Non-Conditional Factors	Factors that affect asset performance due to its operating circumstances
Principal Result	The most significant result from a collection of results taken over a period of time.
Probability of Failure	The likelihood that a Failure Mode will occur in a given time period
Probability of Consequence	The likelihood that a consequence will manifest due to a failure in each time period.
Risk	Effect of uncertainty on objectives*

Risk management	Coordinated activities to direct and control an organization with regards to risk*
Specific Degradation	Processes inside assets that give a good indication of asset failure

15. GLOSSARY OF ABBREVIATIONS

AAAC	All Aluminium Alloy Conductors
AAL	Anticipated Asset Life
AR$_k$	Risk associated with Asset K
AFM	After Fault Maintenance
ABCB	Air Blast Circuit Breaker
ACAR	Aluminium Conductor Aluminium Reinforced conductor
ACSR	Aluminium Conductor Steel Reinforced conductor
BS EN	British Standards European Norm
CAB	Conventional Air-Blast
CoF	Consequence of Failure
CUSC	Connection and Use of System Code
COMAH	Control of Major Accident Hazards
DGA	Dissolved Gas Analysis
EoL Modifier/ EOLmod	End of Life Modifier
EKP	Economic Key Point
FFA	Furfuraldehyde Analysis
FMEA	Failure mode and effects analysis
FMECA	Failure Modes, Effects and Criticality Analysis
GCB	Gas Circuit Breaker
HILP	High Impact Low Probability
ISO	International Organization for Standardization
MITS	Main Interconnected Transmission System
MVArh	MegaVar Hours
MWh	Megawatt Hours
MMI	Maximum Multiple Increment technique
NETS SQSS	National Electricity Transmission System Security and Quality of Supply Standards
NEDeR	National Equipment Defect Reporting Scheme
N	Number of
NR	Network Risk
NGET	National Grid Electricity Transmission
NARM	Network Asset Risk Metric
OCB	Oil Circuit Breaker
Ofgem	Office of gas and electricity markets
OHL	Overhead line
PAB	Pressurised head Air Blast
PoF	Probability of Failure
RIGs	Regulatory Instructions and Guidance
RTM	Risk Trading Model
SSENT	Scottish and Southern Electricity Networks Transmission
SP-T	Scottish Power - Transmissions
SO	System Operator
SSSI	Site of Special Scientific Interest
SVL	Sheath Voltage Limiter
TEC	Transmission Entry Capacity
TNUoS	Transmission Network Use of System
TO	Transmission Owner
TEC	Transmission Entry Capacity (in MW)
VOLL	Value of Lost Load

16. GLOSSARY OF SYMBOLS

β	Ageing Rate
ϕ	Design Variation Weighting Factor
C_j	Monetised consequence j
C_{MVArh}	Average cost of procuring MVArh from generation sources
C_{SBP}	Annual average system buy price
C_{SMP}	Annual average system marginal price
C_{TNUoS}	Average TNUoS refund cost per MWh
CoF_j	Consequence of Failure Mode
D	Duration or Family specific deterioration
D_d	Circuit damage restoration time
D_f	Unrelated fault restoration time
D_{fm}	Duration of failure mode unavailability
D_m	Protection mal-operation restoration time
D_o	Outage restoration time
D_l	Circuit overload restoration time
EoL	End of Life of a given asset
FV_1	Factor Value
G_c	Generation compensation payment cost
G_R	Cost of generation replacement
i	Failure mode i
j	Probability of Failure Mode Effect
k	A given asset or a family specific deterioration scaling factor
L	Customer connection or substation
L_E	Expected Asset Life
$LTRB$	Long-term Monetised Risk Benefit
MW_D	Annual average true demand of customers disconnected
MW_{GTEC}	The Transmission Entry Capacity of each disconnected generator
MW_W	Weighted quantity of disconnected generation
M_z	A multiplier coefficient
n	A given whole number
N_d	Probability of no damage to another circuit
N_f	Probability of no coincident fault to another circuit
N_l	Probability of not overloading remaining circuit
N_m	Probability of no protection maloperation of another circuit
N_o	Probability of no coincident outage
P	Probability
$P(C_j)$	Probability of consequence j occurring during a given time period
$P(C_j/F_i)$	Conditional probability of consequence j arising as a result of failure mode i occurring
P_d	Probability of damage to another circuit
$P(D_i)$	Probability of failure mode i being detected and action being taken before consequence j materialises
P_f	Probability of a coincident fault to another circuit
$P(F_i)$	Probability of failure mode i occurring during the next time interval
P_l	Probability of overloading remaining circuit
P_m	Probability of protection maloperation of another circuit
P_o	Probability of coincident outage
P_{oc}	Probability of disconnection
Q	Capacity of the Asset in MVAr

$R_{boundary}$	Boundary transfer risk cost
$R_{customer}$	Customer disconnection risk cost
R_F	Requirement factor for compensation equipment
R_{RC}	Reactive compensation risk cost
S_C	Particularly sensitive COMAH sites
S_E	Economic key point
S_i	Component score for OHL conductor samples
$S_t \, or \, S(t)$	The cumulative probability of survival until time t
S_T	Transport hubs
$S_{t+1} \, or \, S(t+1)$	The cumulative probability of survival until time $t+1$
t	A given time period
V	Vital infrastructure disconnection cost
V_C	Disconnection cost for COMAH sites
V_E	Disconnection cost for economic key point
V_T	Disconnection cost for transport hubs
W_{FAM}	Family weighting score for overhead line conductors used in EOL modifier calculations
X	Number of circuits supplying a connection after an asset failure
Z	The number of customer sites where X is at its minimum value, X_{min}