NGET Process Appendix

To accompany Issue 16

VERSION CONTROL

VERSION HISTORY

Date	Version	Comments
28/04/17	1	Submission

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GLOSSARY

Term	Definition
Condition Inspection	An inspection which provides information on the state of an asset which is including in the calculations for probability of failure. An inspection can be both Remedial and Condition.
Constant Failure Mode	A failure mode with a constant rate of failure irrespective of age or time since last intervention.
EOL Modifier	End of Life Modifier incorporates condition information for an asset generating an effective age which is used to generate a probability of failure.
Event	Something which can happen as a result of a failure mode and has a monetised consequence associated with it.
Failure Curve	The cumulative probability density function generated for a particular failure mode using parameters supplied in the FMEA.
Failure Mode	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. Each failure mode needs to be mapped to one or more failure mode events.
Increasing Failure Mode	A failure mode which has an increasing probability of occurring over time.
Lead Asset	One of the following: 1. Circuit Breakers 2. Transformers 3. Reactors 4. Underground Cable 5. Overhead Lines a. Conductor b. Fittings
Monetised Consequence	The cost to the transmission system of a particular event occurring. Broken into non-overlapping types: Financial, Safety, Environment, System.
NGET	National Grid Electricity Transmission
NOMs	Network Output Measures
Random Failure Mode	A failure mode with a constant rate of failure irrespective of age or time since last intervention.
Remedial Action	Action taken on finding a failure and before the asset is required to operate.
Remedial Inspection	An inspection, like an operational test, which tests whether an asset is functioning. If the asset isn't functioning action is taken to either remove the asset from the system or repair the functional failure. An inspection can be both Remedial and Condition.

PURPOSE OF PROCESS APPENDIX

Ofgem has requested modifications to the existing RIIO methodology to better facilitate achievement of the NOMs objectives. The current method assigns condition scores and criticality categories to assets, aiming to ensure the distribution of scores and criticalities remains within acceptable bounds. The required method is one where the probability of failure for an asset is understood, together with a monetised consequence of failure. This generates a risk score which can be aggregated across the network to yield Network Risk.

This document explains the NGET Risk Methodology developed to meet this objective and how specific requirements contained in Ofgem's 'Direction to Modify NOMs Methodology' will be delivered.

In developing the methodology, NGET has borne the following Ofgem guidance in mind:

"The Methodology shall be designed to facilitate the NOMs Objectives and to comply with the principles of transparency and objectivity as described below:

- ***Transparency** - the Methodology should contain sufficient detail to explain to a competent independent assessor why and how investments are prioritised and how efficient levels of past and future expenditure are determined. The publicly available elements of the NOMs should enable a competent reader without access to sensitive information or data to form a theoretical view on performance of a 'Generic TO'1.*

- ***Objectivity** - the Methodology will be unambiguous and enable any two competent independent assessors (with access to the same input data) to arrive at the same view of licensees' performance (over- delivery, under-delivery, or on target delivery) and to identify and quantify the relevant factors contributing to performance."*

In addition, the team developing the methodology within NGET have worked to the following guiding principles:

- **The "system" provides a consistent response** – Distinct assets of the same type in an identical state and located within equivalent network topologies should generate equal monetised risk scores. The term "system" refers not only to the model but to the end to end process of collecting data, making any assumptions, using the model and interpreting results.

- **Is able to improve over time with new data** – Our understanding of assets and how they deteriorate, due environmental conditions, usage or time, is continuously improving. A suitable methodology must be flexible enough to incorporate future knowledge making better predictions in a transparent and auditable manner.

- **As simple as required but not simpler** – when choosing between simple and more complicated approaches we have chosen the simpler approach. Except where a more complex approach demonstrably improves predictive power.

- **Distil engineering experience and judgement from across NGET** – Within NGET we have access to many decades of globally recognised technical knowledge and experience. During the development process we have spoken to and incorporated feedback from respected engineers and asset managers.

- **Use proven engineering and mathematical techniques** –The FMEA methodology and the use of standard statistical techniques for modelling reliability are proven and have a long track record in electricity transmission and across many industries.

APPENDIX OVERVIEW

ASSET (A) (1.1.1.)

An asset is defined as a unique instance of one of the five types of lead assets:

1. Circuit Breakers
2. Transformers
3. Reactors
4. Underground Cable
5. Overhead Lines
    a. Conductor
    b. Fittings

Overhead Line and Cable routes are broken down into appropriate segments of the route. Each Asset belongs to an Asset Family. An Asset Family has one or more material Failure Modes. A material Failure Mode can lead to one or more Events.

MATERIAL FAILURE MODE (F) (1.1.2.)

The 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 an Event with a monetised consequence. Each failure mode needs to be mapped to one or more Events.

Each failure mode (F_i) needs to be mapped to one or more Events (E_j) and the conditional probability the Event will manifest should the failure occur $P(E_j|F_i)$.

PROBABILITY OF FAILURE P(F) (1.1.3.)

Probability of failure ($P(F_i)$) represents the probability that a Failure Mode will occur in the next time period. It is given by:

$$\boldsymbol{P}(\boldsymbol{F_i}) = \frac{\boldsymbol{S_t} - \boldsymbol{S_{t+1}}}{\boldsymbol{S_t}}$$

Equation 1

$where:$

$P(F_i) = the\ probability\ of\ failure\ mode\ i\ occurring\ during\ the\ next\ time\ interval$

$S_t = the\ cumulative\ probability\ of\ survival\ until\ time\ t$

$S_{t+1} = the\ cumulative\ probability\ of\ survival\ until\ time\ t+1$

It is generated from an underlying parametric probability distribution or failure curve, taking into account any remedial inspections. The nature of this curve and its parameters (i.e. increasing or random failure rate, earliest and latest onset of failure) are provided FMEA. The probability of failure is influenced by a number of factors, including time, duty and condition.

EVENT (E) (1.1.5.)

The monetised value for each of the underlying Financial, Safety, System and Environmental components of a particular event e.g. Transformer Fire. Each E_j has one or more F_i mapped to it. An Event can be caused by more than one Failure Mode, but an Event itself can only occur once during the next time period. For example, an Asset or a particular component is only irreparably damaged once.

PROBABILITY OF EVENT P(E) (1.1.6)

If Event *j* can be caused by n failure modes, then $P(E_j)$ the probability of event *j* occurring in the next time interval is given by:

$$\boldsymbol{P\left(E_j\right) = 1 - \prod_{i=1}^{m}(1 - P(\mathrm{MF}_i) \times P\left(E_j \middle| F_\mathrm{i}\right)}$$

Equation 2

$where$:

$P\left(E_j\right) = Probability\ of\ Event\ j\ occurring\ during\ a\ given\ time\ period$

$P(MF_i) = Probability\ of\ material\ failure\ mode\ i\ occurring\ during\ the\ next\ time\ interval$

$P\left(E_j \middle| F_i\right) = Conditional\ probability\ of\ Event\ jgiven\ F_i\ has\ occured$

The derivation of $P(MF_i)$ from $P(F_i)$is explained in section **Error! Reference source not found.** as part of t reatment of inspection and detection.

ASSET RISK (1.1.7.)

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

$$\boldsymbol{Asset\ Risk(A_k) = \sum_{j=1}^{n} P(E_j) \times E_j}$$

Equation 3

$where$:

$P\left(E_j\right) = Probability\ of\ Event\ \mathrm{j}\ occurring\ during\ a\ given\ time\ period$

$E_j = the\ monetised\ Event\ j$

$n = the\ number\ of\ Events\ associated\ with\ Asset\ k$

NETWORK RISK (3.5.)

Network Risk is the sum of individual Asset Risks and is given by:

$$\boldsymbol{Network\ Risk}(\boldsymbol{NR}) = \sum_{\boldsymbol{k=1}}^{\boldsymbol{m}} \boldsymbol{A_k}$$

Equation 4

$where$:

$$A_k = Asset\ Risk\ for\ asset\ k$$

RISK IS MODELLED AT AN ASSET LEVEL

We calculate Risk at an Asset level, assuming asset failures are independent, this allows aggregation and comparison of risk across geography and asset type.

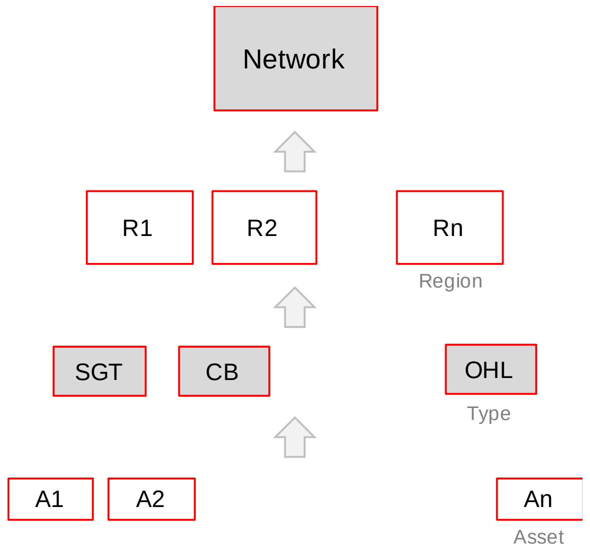


Figure 1

- Asset failures are independent of other Assets.
- Failure modes for a particular asset are independent
- Events given a failure mode are not independent – the same event can arise through different failure modes
- The model does not include circuit and network information
- Asset specific system consequences act as a proxy for this information

ASSETS TRANSITION FROM A FUNCTIONAL TO A FAILED STATE

Assets transition from a functional to a failed state via Failure Modes. Material failure modes can lead to Events which have monetised Consequences..

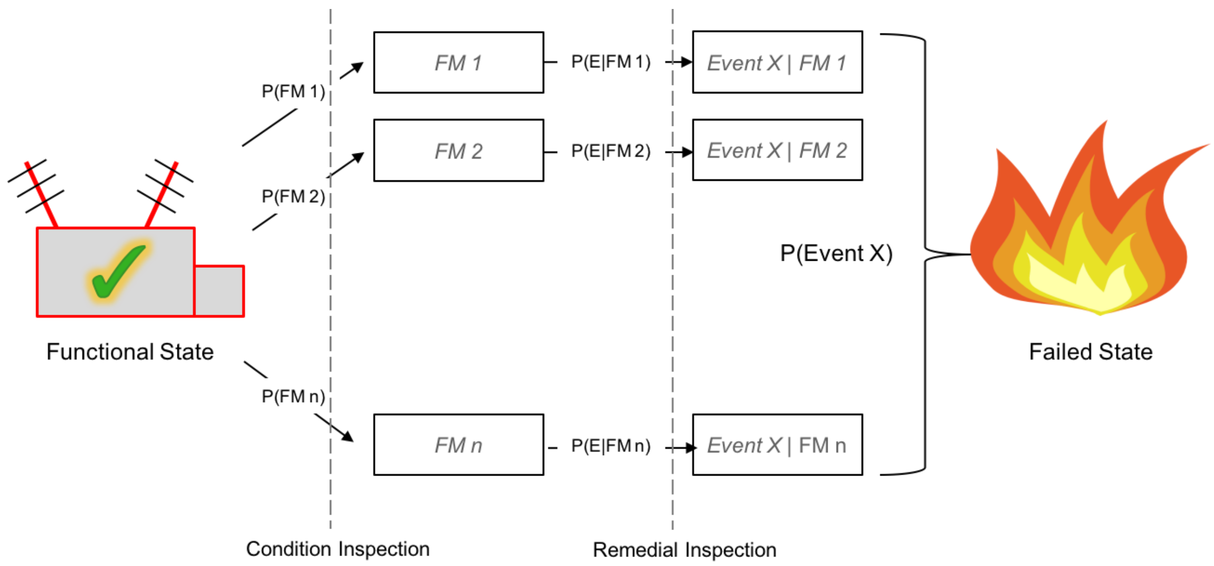
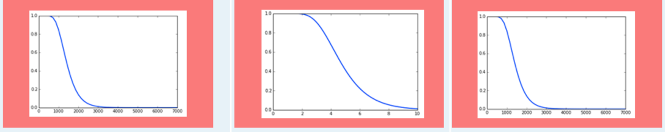


Figure 2 An SGT has many failure modes which can lead to a Tx fire. A fire is an Event with a monetised consequence.

FMEA IDENTIFIES RELEVANT FAILURE MODES

The FMEA process identifies failure modes, interventions which address them and provides the parameters required to generate a probabilistic model. Interventions for particular Failure Modes are identified during the FMEA process.

Asset	Transformer	Circuit Breaker	Reactor
Failure Mode	Latch Failure	Bush. Dielectric Failure	Dominant FM 3
Basic Maintenance	✔	✗	✗
Major Maintenance	✔	✗	✔
Replacement	✔	✔	✔
Refurbishment	✔	✔	✔
Inspection	✗	✗	✗



Interventions

Figure 3

FAILURE CURVES ARE GENERATED FROM THE PARAMETERS SUPPLIED IN THE FMEA

The FMEA process specifies the nature of particular failure modes, for example if it's increasing or random, whether any inspection or condition information can be used to update the effective age of an asset.

			Events				Interventions									
FMEA_Family	Item	Failure Mode	F	S	E	R	Insp.	Basic	InterM	Major	Refurb	Replace	DGA	Pattern	Earliest	Latest
Tap Changer	Tapchanger Selector 9 yrs	fail to operate	3	4	1	1	0	0	0	1	0	0	0	Increasing	9	12
Transformer	Cooling System	reduced cooling capacity	1	1	1	3	1	1	0	1	0	0	0	Increasing	3	11
QB	Cooling System	reduced cooling capacity	1	1	1	3	1	1	0	1	0	0	0	Increasing	3	11

1. Increasing FMs* are modelled using a Weibull curve

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

2. The parameters for the curve are determined by using data supplied in the FMEA to fit the eqn. below.

$$\ln(\ln(\frac{1}{1 - F(t)})) = \propto \ln(t) - \propto \ln \beta$$

3. The curve can then be used to generate PoFs

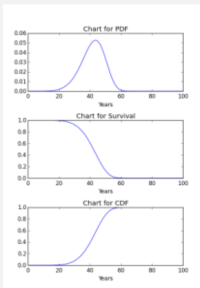


Figure 4

PROBABILITY OF MATERIAL FAILURE

A failure is only material[1] if it occurs before an asset is required to operate and both occur before the next maintenance or replacement intervention. We are interested in $P(F<T)P(E<T|E>Tf)$, where:

- T denotes the time until next intervention,
- F time to failure,
- E the time until the failed functionality is required to by the asset to operate.

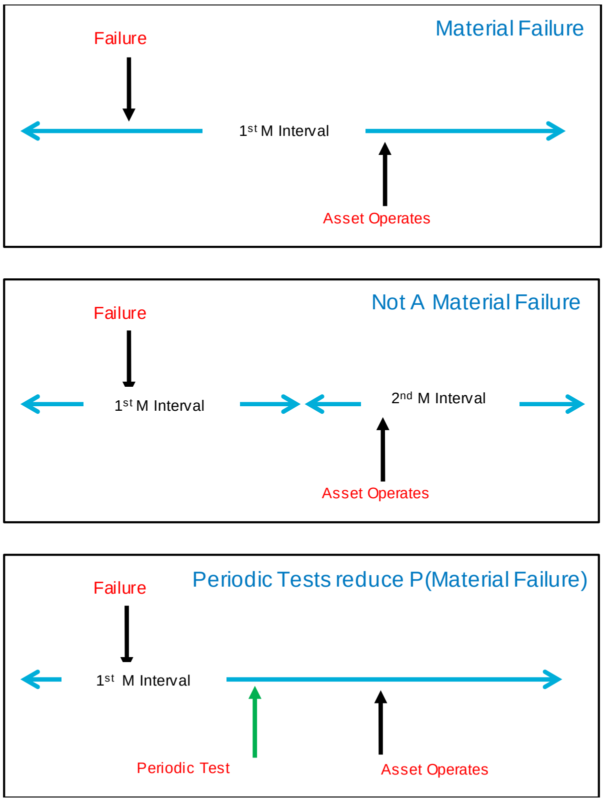


Figure 5

Periodic tests or operations can spot failures before an asset is required to operate, therefore reducing the probability of a material event.

[1] Doesn't lead to an Event(E) but will still require repair

In general the probability of material failure in any given year is given by:

$$\boldsymbol{P(Material\ Failure) = \left(\sum_{k=1}^{n\times m} pq^{k-1}z^{nm-k}\right) \times (1 - z^{m}) + \sum_{k=1}^{m} pq^{k-1}\left(1 - z^{n-k}\right)}$$

Equation 5

$where$:
$n = years\ since\ last\ inspection, intervention\ or\ repair$
$m = number\ of\ sub - intervals\ of\ a\ year$[2]
$p = probability\ of\ failure\ in\ relevant\ sub\ interval$
$q = 1 - p$
$y = probability\ of\ asset\ operating\ in\ sub - interval$
$z = 1 - y$

When assets are annually inspected the above equation simplifies to:

$$\boldsymbol{P(Material\ Failure) = \sum_{k=1}^{m} pq^{k-1}\left(1 - z^{n-k}\right)}$$

Equation 6

since immediately after an inspection $n = 0$.

When a failure mode immediately results in an Event then P(Failure) and P(Material Failure) are equal.

By treating inspections like this we can estimate the inspection frequency required to maintain a given P(Material Failure) as an asset ages and maintain mitigated risk. This also sets the lower bounds of a continuous monitoring system which is not to the rate of inspection but the time taken to complete a remedial action.

[2] for example we can break a year into 365 days so m = 365. The shorter the sub-interval, the greater run time.

TREATMENT OF INSPECTION AND DETECTION (1.1.4)

CONCEPTUAL MODEL

Two separate aspects of Inspections effect the outcome of the model in different ways. Inspections provide condition information which can be used to generate a more accurate P(Failure) and/or check if an asset is working as expected at time of the inspection (in the form of operational tests).

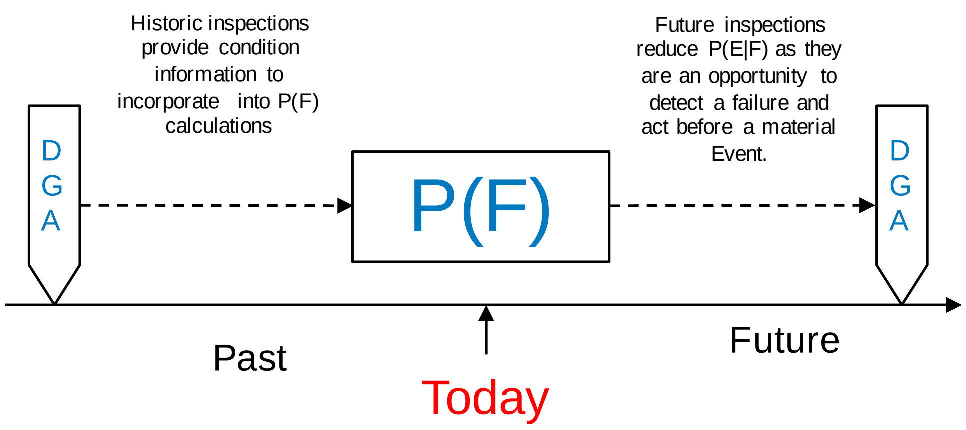


Figure 6 - Inspections provide condition infomation and an opportunity to fix hidden failures.

Operational tests or inspections reduce the probability of material Events if Action is taken when a defect is identified and before the Asset is required to function on the network.

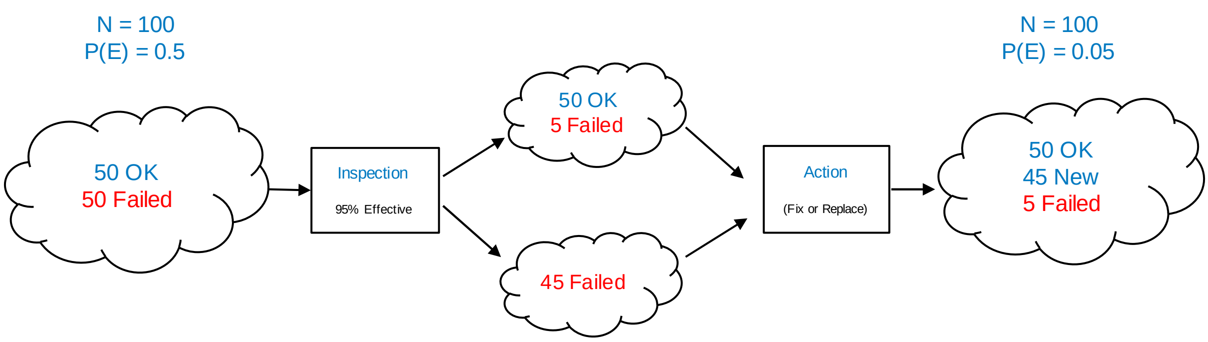


Figure 7

For example a CB may have a hidden drive train fault which means it will not operate when required to break a fault current. This would be a significant event but a remedial inspection would uncover the hidden failure allowing it to be repaired before a potentially catastrophic event.

PROBABILITY OF FAILURE (2.)

PROCESS FOR FMEA (2.1)

The process for identifying failure modes uses component studies for each asset class to understand the asset risk.

For each component, each failure mode (that is each component) is assessed to determine:

- Detection: effectiveness of detection, where applicable
- Event: all possible events including the probability of a particular event. It is connected with each failure mode, whichever type that failure mode may be
- Probability of Failure
- Type of Failure Mode (P-F, utilisation, random)

For the purpose of calculating Asset Risk, the FMEA process generates the following outputs by Asset Type:

- List of significant failure modes both within life and at end of life
- Identification of interventions which address each failure mode
- Potential events should a failure mode occur and the likelihood of the event occurring given the failure mode
- The financial, safety, environment and reliability consequences resulting from the event
- Classification of a failure mode as time based, duty or random (or a combination)
- For increasing time based failure modes expected earliest (2.5% of the population) and latest onset of failure (97.5% of the population) and the most appropriate underlying density function (Weibull, bi-normal) since installation or the latest relevant intervention
- For random failure modes, the random rate of failure. These are known failure modes and are expressed as a % failures per year
- Inspections which aim to detect potential failures before they occur, their likelihood of success and their period of validity

An internal procedure (TP237) has been written for FMEA which is kept confidentially in the Licnsee Specific Appenidx for NGET.

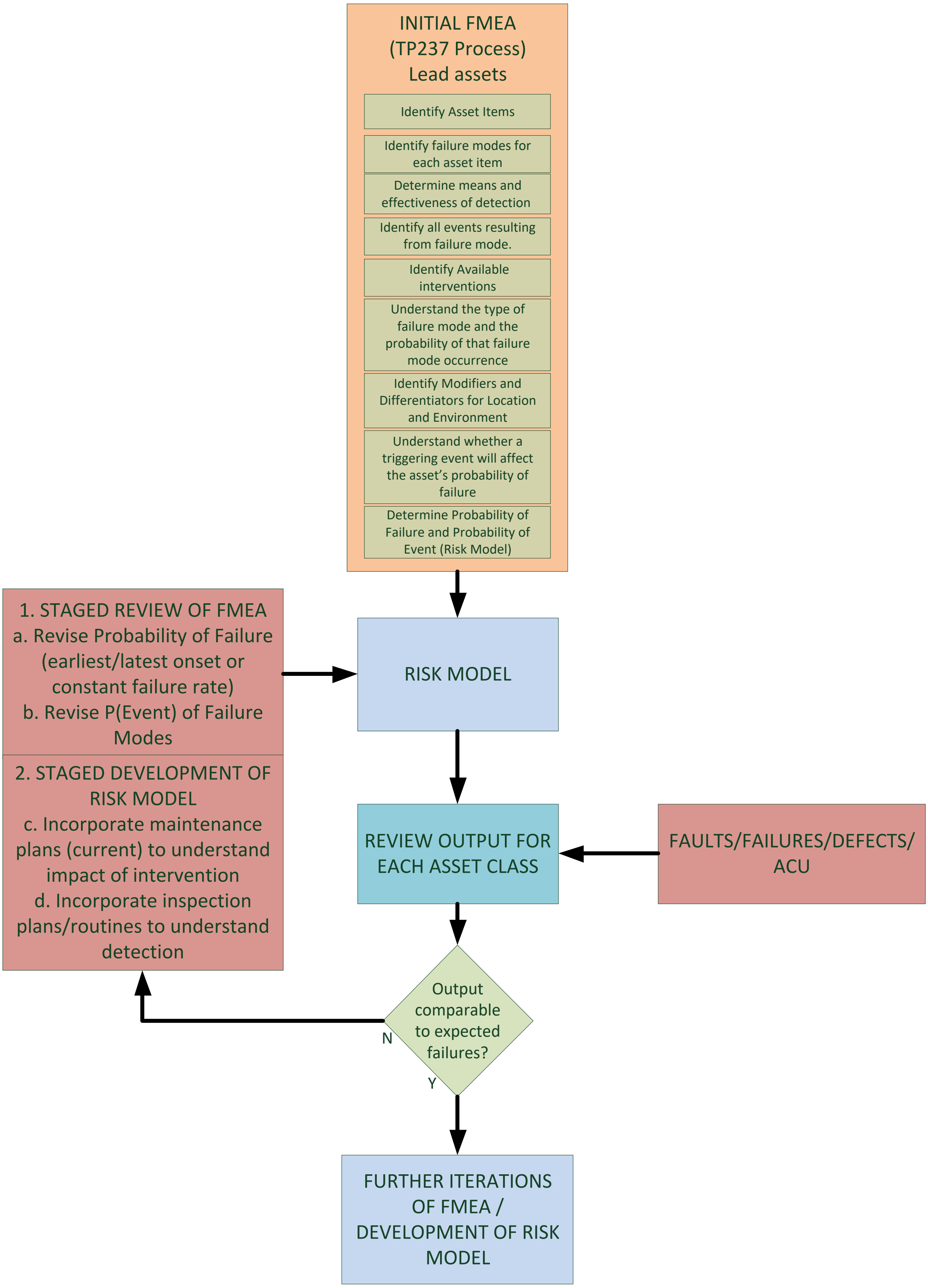

INITIAL FMEA
(TP237 Process)
Lead assets
Identify Asset Items
Identify failure modes for each asset item
Determine means and effectiveness of detection
Identify all events resulting from failure mode.
Identify Available interventions
Understand the type of failure mode and the probability of that failure mode occurrence
Identify Modifiers and Differentiators for Location and Environment
Understand whether a triggering event will affect the asset's probability of failure
Determine Probability of Failure and Probability of Event (Risk Model)
1. STAGED REVIEW OF FMEA
a. Revise Probability of Failure (earliest/latest onset or constant failure rate)
b. Revise P(Event) of Failure Modes
2. STAGED DEVELOPMENT OF RISK MODEL
c. Incorporate maintenance plans (current) to understand impact of intervention
d. Incorporate inspection plans/routines to understand detection
RISK MODEL
REVIEW OUTPUT FOR EACH ASSET CLASS
FAULTS/FAILURES/DEFECTS/ ACU
Output comparable to expected failures?
N
Y
FURTHER ITERATIONS OF FMEA / DEVELOPMENT OF RISK MODEL

Figure 8

FAILURE MODES (2.2.)

FMEA takes into account the effectiveness of the detection technique, determined as a percentage, as not all failure modes will result in 100% detection from the inspection technique. Indeed for some failure modes, effective detection is technically not possible or economically unviable.

DETECTING POTENTIAL TO FUNCTIONAL FAILURE MODES

As this failure mode is time based, the detection method will only be valid for a certain duration following the detection activity, i.e. the risk is reduced for a fixed time period and then increases until the next inspection or intervention.

DETECTING UTILISATION FAILURE MODES

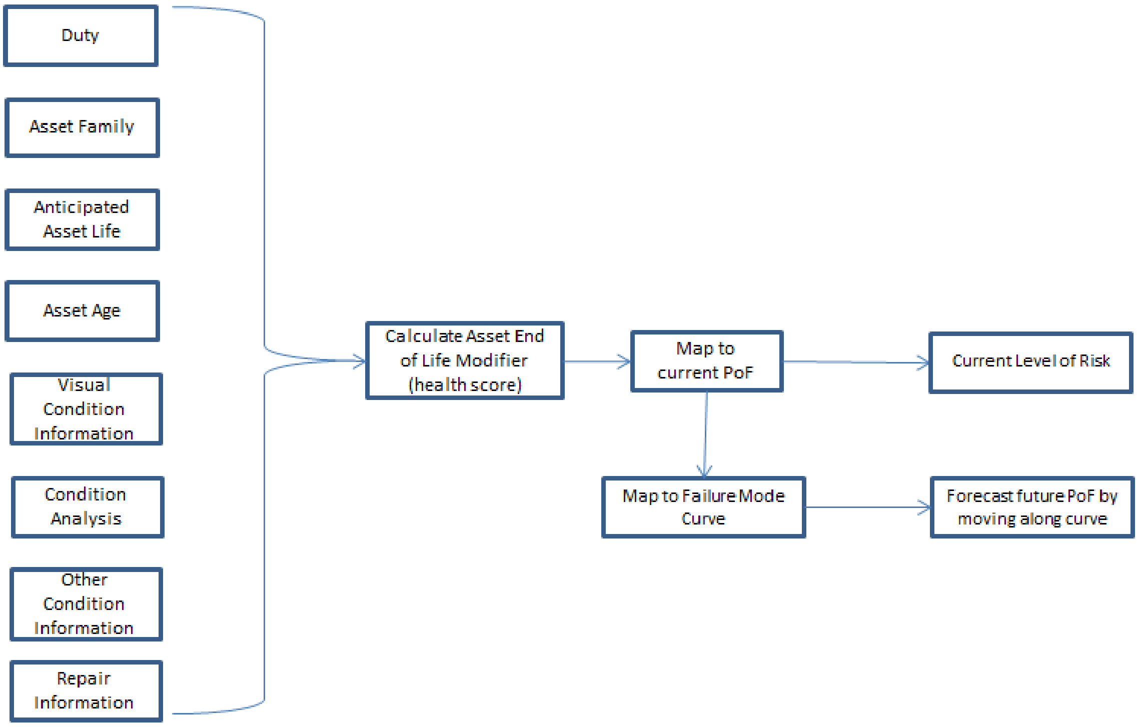
These failure modes are based upon the utilisation of particular assets. For example, the deterioration of assets such as circuit breakers is based upon the number of operations it carries out. It is possible to forecast the expected duty for individual assets and hence interventions can be planned before the risk increases above a specified limit.

DETECTING RANDOM FAILURE MODES

By definition these failure modes are difficult to detect until the failure actually happens. Forensic analysis of failed assets or components can provide valuable information about the failure mode and its future detection the interventions that could prevent it.

PROBABILITY OF FAILURE (2.3.)

The process illustrated below will be used to determine the probability of failure of each asset. In particular we will need to translate from the end of life modifier that will be determined in the subsequent sections. This will be done by translating through a probability mapping step, so that the appropriate end of life curve can be used to determine the probability of an asset having failed.



DERIVING PARAMETERS FOR PROBABILITY DISTRIBUTIONS

The failure modes and effects analysis defined an end of life curve for each asset family. 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 R&D 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.

The end of life failure curve will be based in terms of the data points corresponding to the ages at which 2.5%, and 97.5% of failures occur. The method for determining the end of life curves was explained in the failure modes and effects analysis section of this document.

Typically within each lead asset group there will be separate end of life curves determined for each family grouping. Assignment to particular family groupings is through identification of similar life limiting factors.

MAPPING END OF LIFE MODIFIER TO PROBABILITY OF FAILURE (2.3.2.)

Each lead asset within the NOMs risk model has an end of life failure modifier score. These scores need to be translated to a probability on the relevant failure mode curve. This end of life probability of failure (PoF) is determined from the end of life (EOL) modifier, which itself is determined from the asset's current condition, duty, age and asset family information. The EOL modifier has been developed to have a strong relationship with the likelihood of asset failure but is not itself a PoF over the next year.

A probability mapping function is required to enable mapping from an EOL modifier to a conditional PoF. The figure below illustrates distributions representing the end of life failure mode for a population of transformer. The 50% point on the cumulative distribution function (green) indicates the anticipated asset life (AAL). The conditional PoF at the AAL can be determined from the red curve in the figure below (approximately 10% per year). We can use this as an initial value in the mapping function, such that an EOL modifier of 100 is equivalent to a 10% conditional PoF.

PoF can't be utilised at an individual asset level to infer individual asset risk, and therefore the PoF values need to be aggregated across the asset population in order to support the calculation of risk. Over a population of assets at a given a PoF we have an expectation of how this PoF will continue to deteriorate over time, duty or condition. This is shown by the conditional PoF curve in red.

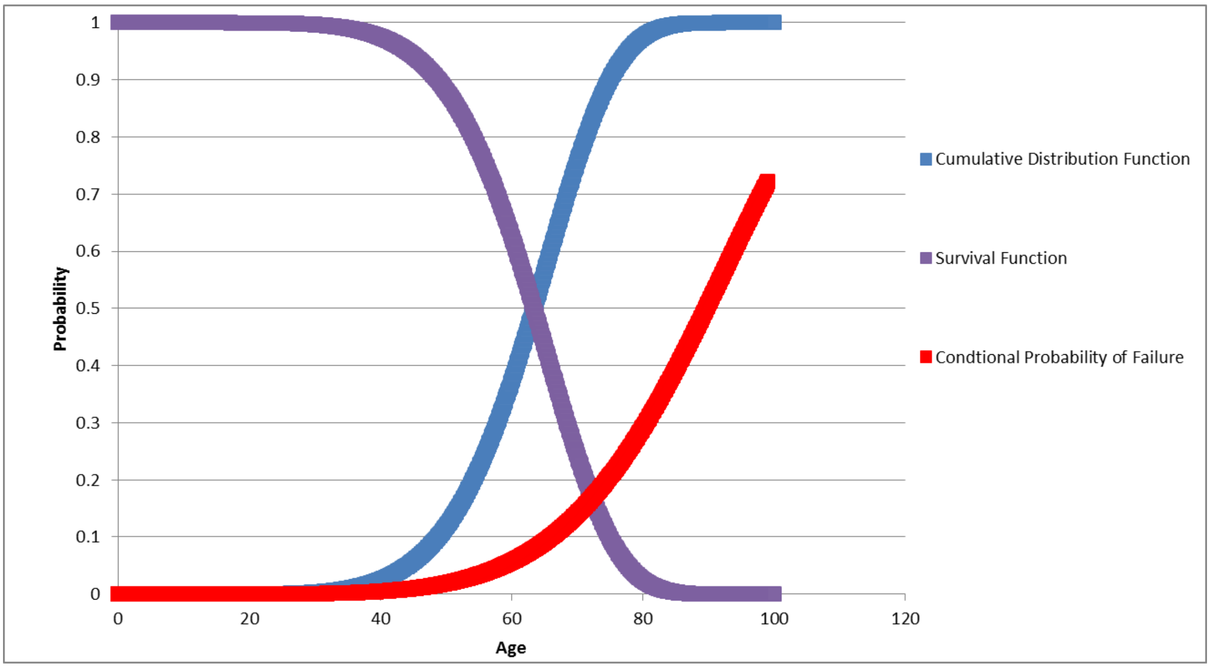


Figure 9

The development of a methodology that maps the EOL modifier to PoF needs to consider the actual number of failures that we experience, it should then be validated against the expected population survival curve and it should satisfy the following requirements:

- High scoring young assets should be replaced before low scoring old assets. *The mapping function achieves this objective because high scoring assets will always reach their AAL quicker than those of low scoring assets.*
- When two assets of similar criticality have the same EOL modifier score then the older asset should be replaced first. *The mapping function will assign the same PoF to both assets, so they reach their respective AAL at the same time. In practice the planner could prioritise the older asset for replacement over the younger asset without penalty.*
- When an asset is not replaced the PoF should increase. *The EOL modifier score reflects the condition of the asset, and will therefore increase over time. This means the PoF will also increase.*
- A comprehensive and steady replacement programme will lead to a stabilisation of the population's average PoF. *The proposed methodology will satisfy this requirement as worsening PoF would be offset by replacements.*
- The PoF and resulting risks must be useful for replacement planning. *The proposed methodology is validated against the expected survival function, so should be compatible with existing replacement planning strategies.*
- Outputs should match observed population data. The expected survival function for the population is already identified based on known asset deterioration profiles and transmission owner experience. *The mapping to PoF method is validated against this expected population statistic.*

In the following example we will consider how the conditional mapping function is derived for a transformer, and then how the mapping curve parameters can be systematically adjusted through a process of validation and calibration against the expected population's survival curve.

The mapping function is given by the following exponential function.

$$Conditional\ PoF = \exp(k * EOLmod^{\alpha}) - 1$$

Equation 7

The parameter α is tuned so that the deterioration profile over the population is consistent with the expected survival function for the relevant population of assets. The expected survival function is given by the FMEA earliest and latest onset of failure values, which have been determined though the transmission owner experience using all available information such as manufacturer data and understanding of asset design.

The parameter k scaling value ensures that for an EOL modifier score of 100 the expected conditional PoF is obtained (given as β in the formula below). The formula is given by:

$$k = ln\left(\frac{1+\beta}{100^{\alpha}}\right)$$

Equation 8

The PoF mapping function is shown in the figure below for a transformer with α=1.7 and β=10%.

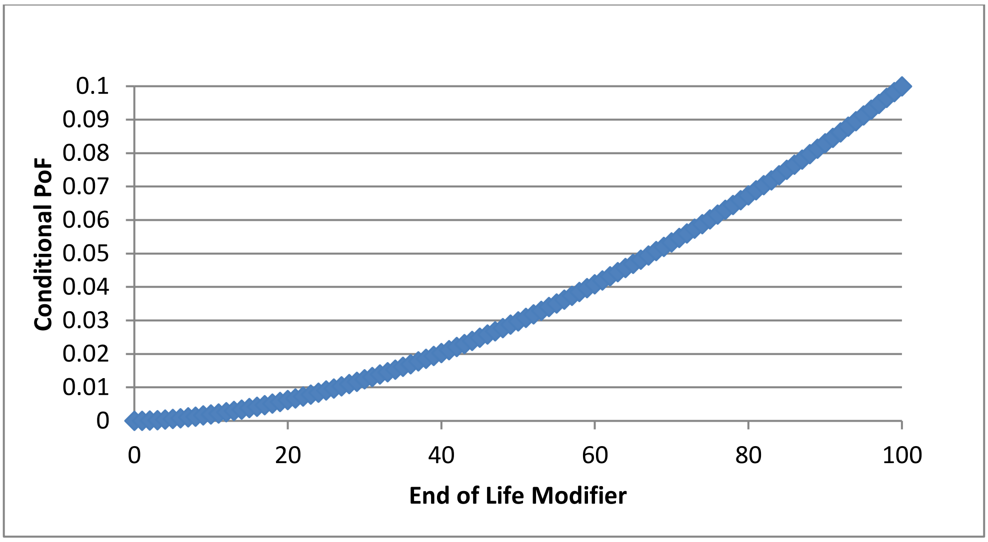


Figure 10

DETERMINING ALPHA (α) AND VALIDATION

To tune the parameters and validate the approach we need to determine the Predicted Actual Age at Failure (PAAF) for each asset, so that we can derive a population survival curve. Using conditional PoF an Equivalent Age (EA) is identified using the red curve in Figure 1 above. The PAAF calculation also needs actual age (Age) and the AAL of the asset's population.

$$PAAF = \text{Age} + (\text{AAL - EA})$$

Equation 9

The EOL modifier score for an individual asset puts it on a conditional PoF curve n years away from the AAL. This n years value can be interpreted as the difference between the AAL and the equivalent age of the asset (AAL – EA). Combining with actual age gives the Predicted Actual Age at Failure, as shown in the formula.

The PAAF can then be used to generate a survival curve that indicates the percentage of the population that is still surviving at a given age. The figure below shows an example modelled transformer survival curve based the on PAAF (blue) overlaid with the expected survival curve generated from the FMEA curve (red). The modelled conditional PoF is observed to give a near perfect fit to the expected survival curve up to 63 years old, which happens to be about the AAL for this asset type. Post 63 years old the trend diverges from the expected survival curve. The post 63 years old section of the survival curve is not as well understood, as we don't have operational experience at this older age range and therefore have no particular reason to expect a match to the survival curve. The linear appearance of the older section of the modelled survival curve (blue) is driven by a large population of transformers that are all around a similar age of 49 years old and have a relatively even spread of EOL modifier scores.

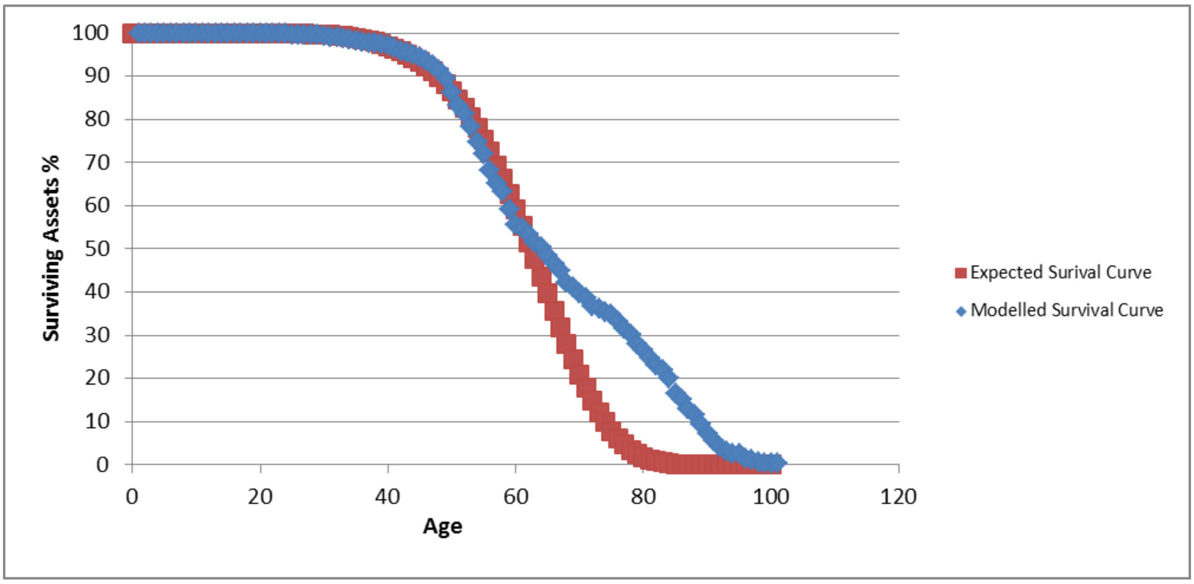


Figure 11

DETERMINING BETA (β) AND VALIDATION

Beta (β) sets the maximum conditional PoF which would be expected for an asset that has reached its AAL. As described in the earlier section an initial value can be determined from the FMEA end of life failure curve earliest and latest onset values. A value of 10% was chosen for transformers, although there is a scope to tune this value using failure data. The total PoF across the population can be obtained by summing the individual conditional PoFs; this is then compared to the observed failures noting that many assets are replaced before they fail. In the case of transformers the sum of conditional PoF gives 5 transformer failures per year. Each year we actually experience 2 transformer failures, but replace 16. It therefore seems reasonable that if we didn't replace these 16 transformers then we might experience 5 failures each year. The value for β can be tuned such that the number of failures is similar to what is actually observed, but any tuning needs to be performed in conjunction with the parameter α.

The parameters alpha (α) and beta (β) are both calibrated by considering population level statistics. In the same sense the PoF or risk is only meaningful when aggregated across the asset population.

OIL CIRCUIT BREAKER CONDITIONAL POF MAPPING EXAMPLE

The analysis described above was repeated for Oil Circuit Breaker (OCB) EOL modifier scoring data in order to validate and quantify the proposed method against expectation based on transmission owner experience. We map the EOL modifier values to a conditional PoF using a similar function to that shown in Figure 1 above, noting that the value of α and β will be specific to this OCB asset type. For the purpose of implementing this methodology we assume that the conditional PoF is β=10% per year for an EOL modifier score of 100. We also assume an initial value of α that will be adjusted.

Using the same method described above for transformers we determine PAAF for each OCB on the network. Plotting these PAAF values as a survival curve, overlaid with the expected survival curve, allows us to quantify the model against expected asset deterioration and provides a mechanism for tuning the mapping parameter α. The modelled survival curve shown in the figure below has been produced with α=2.1 and β=10%. The model follows the expected survival curve of OCBs across the life of the asset.

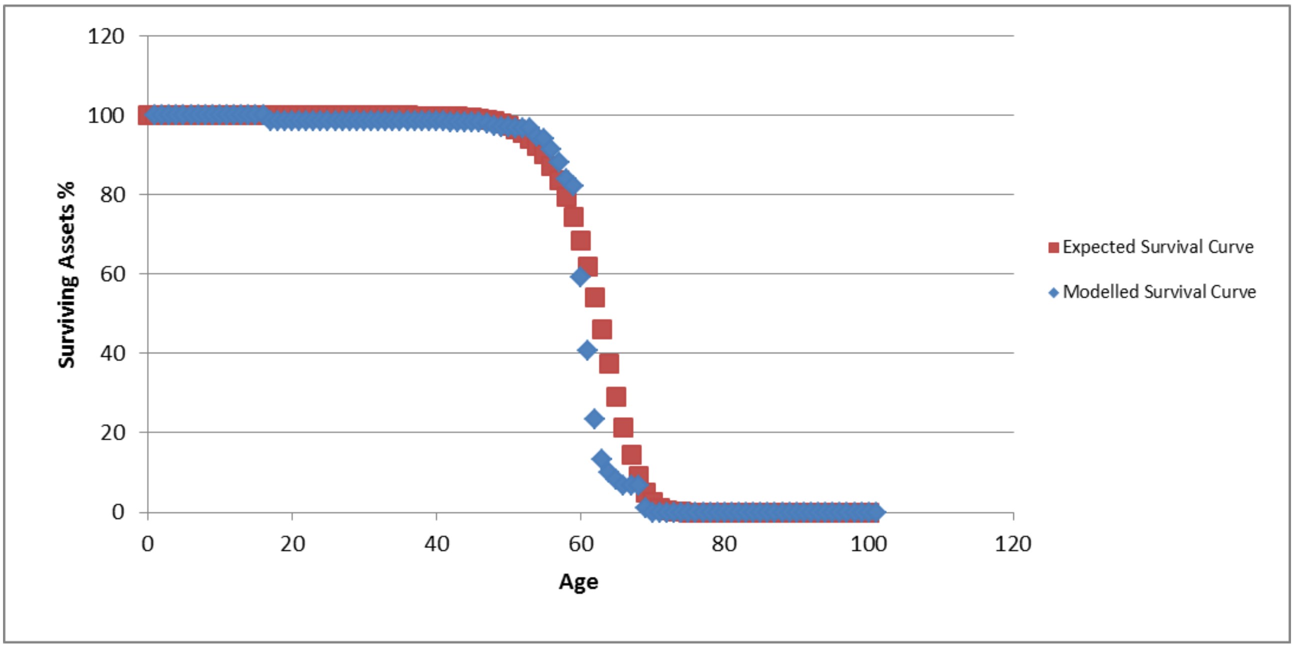


Figure 12

CALCULATING PROBABILITY OF FAILURE (2.3.3.)

As described above the probability of failure curve is based in terms of two data points that correspond to the ages at which specific proportions of the asset's population is expected to have failed. Using these data points we can construct a cumulative distribution function *F(t).* The survival function is given as: S(t) = 1-F(t). The conditional probability of failure is then given by the following formula, where t is equivalent age in the case of end of life failure modes:

$$PoF(t) = \frac{S(t) - S(t+1)}{S(t)}$$

Equation 10

In order to calculate the end of life probability of failure associated with a given asset, the asset will need to be assigned an end of life modifier. This end of life modifier is derived from values such as age, duty and condition information where it is available. In the absence of any condition information age is used. The service experience of assets of the same design and forensic examination of decommissioned assets may also be taken into account when assigning an end of life modifier. Using the end of life modifier we can then determine an asset's equivalent age and then map onto a specific point on the probability of failure curve.

The generalised end of life modifier (EOLmod) formula has the following structure for assets that have underlying issues that can be summed together:

$$EOLmod = \sum_{i=1}^{\substack{number\ of \\ components}} C_i$$

Equation 11

Or for transformer assets that are single assets with parallel and independent failure modes the following generalised end of life modifier formula is used:

$$EOLmod = \left(1 - \prod_{i=1}^{\substack{number\ of \\ components}} \left(1 - \frac{C_i}{C_{max}}\right)\right) * 100$$

Equation 12

C_i represents an individual component parameter of the end of life modifier

C_{max} represents the max score that the component can get

For some of the lead asset types the generalised formula will need to be nested to derive an overall asset end of life modifier. For example in the case of OHLs we need to take the maximum of the preliminary end of life modifier and a secondary end of life modifier.

The end of life modifier will range from zero to 100, where 100 represents the worst health that an asset could be assigned. It is then necessary to convert the end of life modifier to a probability of failure to enable meaningful comparison across asset types.

As far as reasonably possible the scores assigned to components of the end of life modifier are set such that they are comparable e.g. are on the same magnitude. This enables the end of life modifier between different assets in the same family to be treated as equivalent. The magnitude and relative difference between scores is set using expert to judgement as there is limited data available. The validation and testing of these scores is described in the testing section of the Common Methodology.

FORECASTING PROBABILITY OF FAILURE (2.3.4.)

Where appropriate and enough historical data exists, a rate multiplier can be applied, so that for each annual time step in forecast time equivalent age is increased or decreased by the rate multiplier time step. The default value of the rate multiplier time step is set as 1.0 per year. This modelling feature will allow high duty assets to be forecast more accurately.

DETERMINING END OF LIFE MODIFIER

CIRCUIT BREAKER PARAMETERS

SCORING PROCESS

Circuit breakers will be assigned an end of life modifier according to the formula below. The maximum of the two components as shown is determined, and it is capped at 100.

$$EOLmod = \max(AGE\_FACTOR, DUTY\_FACTOR, SF6\_FACTOR\ )$$

Equation 13

The EOL modifier is therefore determined based on the maximum of its constituent parts. AGE_FACTOR, DUTY_FACTOR, and SF6_FACTOR are non-dimensional variables with possible values between 0 and 100.

$$AGE\_FACTOR = \mathrm{C}_1\ \times \mathrm{FSDP} \times \frac{\mathrm{Age}}{AAL}$$

Equation 14

- Age: Reporting year - Installation year (years)
- C1: a scaling factor to convert Age to a value in the range 0 to 100. The method for calculating C_1 is described at the end of this section
- *AAL* is the anticipated asset life determined through FMEA analysis. The end of life curve described in the Failure Modes and Affects analysis section can be used to determine *AAL*, which is the 50% point on the respective end of life failure mode curve. The process for deriving these failure mode curves, which we use to determine AAL, are themselves estimated using historical data and engineering judgement. Further explanation is available in the section of this methodology discussing FMEA
- FSDP is a family specific deterioration correction function described below. This is a function multiplier to convert AGE from a linear function to an exponential function. This has the effect of decreasing the relative significance of lower values of AGE

DUTY_FACTOR

The duty of each circuit breaker asset is determined using the following formula:

$$DUTY\_FACTOR = \mathrm{C}_1 \times FSDP \times \max(\left(\frac{(OC)}{(MOC)}\right), \left(\frac{(FC)}{(MFC)}\right))$$

Equation 15

Where:

- *OC* is the current asset operational count
- *MOC* is the expected max asset operational count over a lifetime. For older circuit breakers this is determined through liaison with suppliers, and for newer circuit breakers this is determined during type testing
- *FC* is the current accumulated fault current

- *MFC* is the max permissible fault current over a lifetime. The value for MFC is set to 80% of the value of the maximum rated value for the asset

FC and MFC are determined through liaison with suppliers who confirm operational limits for the mechanism and interrupter.

Note that the DUTY_FACTOR has been normalised to account for variations in the asset life of the circuit breaker family. This normalisation means that the end of life modifier of a circuit breaker from one family can be compared to the end of life modifier of a circuit breaker from a different family. Age and other duty related metrics are important due to the lack of more specific condition information.

FAMILY SPECIFIC DETERIORATION PROFILE (FSDP)

The Family Specific Deterioration profile accounts for the expected deterioration of an asset. This is needed as there is limited availability of Asset Specific condition information. This function is based on duty value D which is given by the following formula:

$$D = \max(\frac{OC}{MOC}, \frac{FC}{MFC}, \frac{AGE}{AAL})$$

Equation 16

The family specific deterioration function is determined using the function:

$$FSDP = e^{k*D^2} - 1$$

Equation 17

This parameter k is determined such that when D=1.0 then *FSDP*=1.0. This gives a value of k=0.694. FSDP is capped at 1.0.

This function ensures that the impact of family specific deterioration is correctly considered in the health score formula.

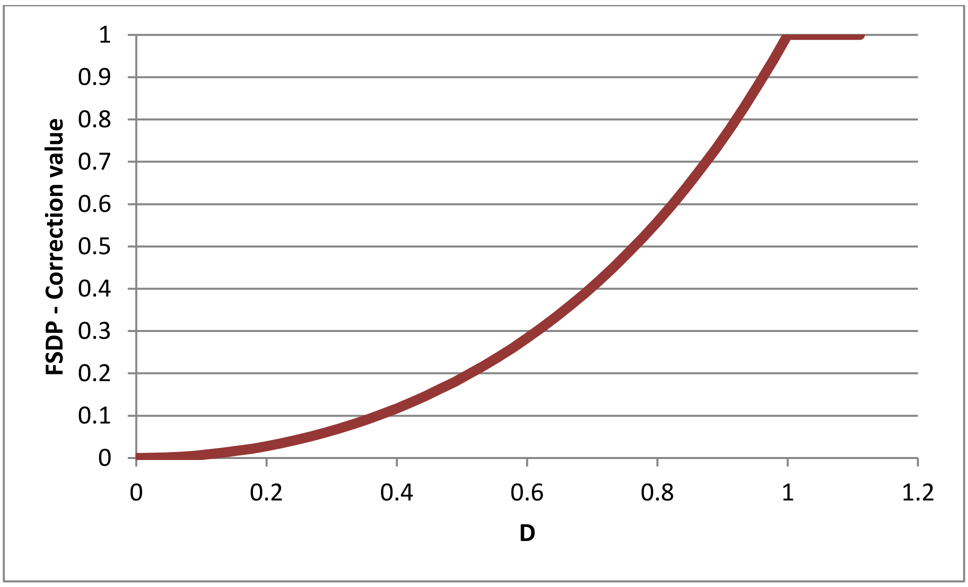


Figure 13

The curve will generate a value from 0 to 1 depending on the duty of the asset. This curve is used within this method due to the lack of condition information, and allows us to accelerate or suppress duty values depending on the deterioration we would expect for that asset family. Note that while the shape of the curve is fixed, the duty value (D) captures family specific factors such as anticipated asset life, maximum fault current and maximum number of operations.

SF6_FACTOR (SF6)

The SF6_FACTOR calculation maps the reported leakage of a circuit breaker to a score of between either 0 or 100. A score of 100 is assigned where major leakage is deemed to have occurred. Leaking time is the time in years that the asset has had a non-zero $Leak_{mass,}$ $Leak_{rate,}$ or $Leak_{combined}$.

$$SF6\_FACTOR = Max(Leak_{Mass},\ Leak_{Rate}, Leak_{Combined}, Leak\ _{Duration} * Leaking\_time)$$

Equation 18

$Leak_{mass}$ is a score dependent on the mass of the mass of SF6 leakage (kg) within the previous financial year.

Mass of Leakage (kg)	**Significance**	**$Leak_{mass}$ Score**
<10kg	Insignificant	0
>=10kg	Significant	60
>=50kg	Major Leakage	75

Table 1

$Leak_{rate}$ a score dependent on proportion of total installed mass of SF6 that has leaked within the previous financial year

$$Leakage\ rate = \frac{Leak_{Mass}}{Asset\ SF6\ Inventory}$$

Equation 19

where Asset SF6 Inventory is the Reported volume of SF6.

Mass of Leakage (kg)	**Significance**	**$Leak_{mass}$ Score**
<5%	Insignificant	0
>=5%	Signifcant	60
>=10%	Major Leakage	75

Table 2

$Leak_{combined}$=100 if both the mass of leakage is >=50kg and leakage rate is >=10%, otherwise $Leak_{combined}$=0

$Leak_{duration}$ ensures that a leaking asset for the last two or five (dependant on current severity of leak) years will be assigned a score of 100.

Leakage Duration	**$Leak_{duration}$ Score**
Leak mass score=60	8
Leak mass score=75	12.5

Table 3

Any asset classified with EOL modifier of 60 or 75 due to SF6 leakage will undergo a significant intervention within a 5 year or 2 year timeframe respectively. It is expected that an asset classified with a health score of

75 today will reach a health score of 100 within 2 years, which has been set-up to reflect legislation that significant SF6 leakers should be repaired within 2 years. The decision over which type of intervention to carry out, *whether that is repair, reconditioning, refurbishment or replacement*, will be *cost justified* for the expected benefit to the consumer. This means that risk will be reduced through the most cost justified intervention, which may not necessarily be asset replacement.

Whilst there are pre-existing technologies that exist to carry out minor repairs to stop SF6 leaks, analysis of these repairs demonstrates that in the majority of instances they are temporary in nature and a further major intervention is then required to permanently repair the asset.

Broadly there are two functional requirements for a Gas Circuit Breaker. Firstly it must be able to break load, and secondly it must be able to retain the Insulating Medium. This is based on the requirements described in the Fluorinated Greenhouse Gases Regulations 2015, which places significant limits on permitted Leakage.

1. Operators of equipment that contains fluorinated greenhouse gases shall take precautions to prevent the unintentional release ('leakage') of those gases. They shall take all measures which are technically and economically feasible to minimise leakage of fluorinated greenhouse gases.

2. Where a leakage of fluorinated greenhouse gases is detected, the operators shall ensure that the equipment is repaired without undue delay. (Chapter 2 Article 3 Sections 2 and 3 from http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014R0517&from=EN)

PROCEDURE FOR DETERMINING C1

This value of this parameter is determined by calculating a value for EOL modifier from historical switchgear data. The C1 value is tuned so that a reasonable translation between historical AHI's, which were calculated under the previous RIIO-T1 volume based methodology, and EOL modifier is achieved. Assets that were classed as AHI1 previously should normally have a score of 100 under the new methodology. This approach is consistent with the theme of the direction, as it enables a translation from previously classified AHI's.

Based on this approach the parameter is fixed as $C1 = 5/6$.

EOL MODIFIER CALCULATION EXAMPLE

The following table shows three assets with example data that will allow us to determine the EOL modifier

Component	Example Asset 1	Example Asset 2	Example Asset 3
Asset Operation Count (*OC*)	350	3000	350
Max Asset Operation Count (*MOC*)	5000	5000	5000
Accumulated Fault Current (*FC*)	400	400	1000
Max Permissible Fault Current (*MFC*)	1400	1400	1400
Anticipated Asset Life (*AAL*)	45	45	45
SF6 leakage (kg)	2	10	1
Age	40	20	15

Table 4

Applying the relevant formula presented in the above sections yields the following output.

	Example Asset 1	Example Asset 2	Example Asset 3
D (in FSDP)	0.89	0.6	0.71
FSDP	0.72	0.28	0.41
AGE_FACTOR	53.19	10.23	11.23
DUTY_FACTOR	16.73	13.94	24.16
SF6_FACTOR	0	60	0
EOL Modifier	53.2	60	24.2

Table 5

The EOL Modifier in example asset 1 is driven by age factor, example 2 is driven by SF6 factor and example 3 is driven by the duty factor (in particular the accumulated fault current).

The EOL modifier calculation proposed here facilitates a reasonable translation from the AHI's utilised within the existing RIIO-T1 methodology. An initial validation has been performed to calculate EOL modifier over a range of assets and then comparing to the AHI determined under the existing methodology.

It should be noted that placing a cap on the age related components of health score would substantially impair the translation from the previous AHI to health score.

TRANSFORMER AND REACTOR PARAMETERS

SCORING PROCESS

The scoring process needs to takes account of the three failure modes – dielectric, mechanical and thermal as well as issues with other components that may significantly impact the remaining service life. The end of life modifier is determined according to the following formula:

$$EOLmod = \left(1 - \left(1 - \frac{DCF}{100}\right)\left(1 - \frac{TCF}{100}\right)\left(1 - \frac{MCF}{100}\right)\left(1 - \frac{OCF}{100}\right)\right) * 100$$

Equation 20

The components of the end of life modifier are assigned using the scoring system described below. The component OCF (other component factor) is a factor that accounts for other issues that can affect transformer end of life. The maximum value of *EOLmod* is 100.

DIELECTRIC CONDITION FACTOR (DCF)

Dielectric condition is assessed using dissolved gas analysis (DGA) results. The score can be increased if the indication is that the individual transformer is following a trend to failure already seen in other members of the family. Where it is known that the indications of partial discharge are coming from a fault that will not ultimately lead to failure e.g. a loose magnetic shield then the score may be moderated to reflect this but the possibility of this masking other faults also needs to be taken into account.

Score	**Dielectric Condition Factor (*DCF*)**
0	All test results normal: no trace of acetylene; normal levels of other gases and no indication of problems from electrical tests.
2	Small trace of acetylene in main tank DGA or stray gassing as an artefact of oil type, processing or additives. Not thought to be an indication of a problem.
10	Dormant or intermittent arcing/sparking or partial discharge fault in main tank.
30	Steady arcing/sparking or partial discharge fault in main tank.
60	Indications that arcing/sparking fault is getting worse.
100	Severe arcing/sparking or partial discharge fault in main tank – likely to lead to imminent failure.

Table 6

THERMAL CONDITION FACTOR (TCF)

Thermal condition is assessed using trends in DGA and levels of furans in oil, . Individual Furfural (FFA) results are unreliable because they can be influenced by temperature, contamination, moisture content and oil top ups, therefore a trend needs to be established over a period of time. The presence of 2 Furfural (2FAL) is usually required to validate the FFA result and the presence or absence of methanol is now being used to validate (or otherwise) conclusions on thermal score. Thermal condition is understood to include ageing and older, more heavily used and/or poorly cooled transformers tend to have higher scores. The score can be increased if the indication is that the individual transformer is following a trend to failure already seen in other members of the family.

Score	Thermal Condition Factor (*TCF*)
0	No signs of ageing including no credible furans >0.10ppm and methanol ≤0.05ppm. The credibility of furan results usually depends on the presence of 2 Furfural (2FAL).
2	Diagnostic markers exist that could indicate ageing (including credible furans in the range 0.10-0.50ppm) but are either not showing a credible progression or are thought to be the result of contamination. The credibility of furan results usually depends on the presence of 2 Furfural (2FAL).
10	Indications or expectations that the transformer is reaching or has reached mid-life for example: credible furans in the range 0.51-1.00ppm or stable furans >1ppm possibly as a result of historic ageing. and/or Raised levels of methane or ethane in main tank DGA consistent with low temperature overheating. and/or Transformers with diagnostic markers resulting from oil contamination (e.g. furans, specifically 2FAL) that may mask signs of ageing.
30	Moderate ageing for example: credible furans consistently > 1ppm with a clear upward trend. and/or Significant overheating fault (steadily rising trend of ethylene in main tank DGA).
60	Advanced ageing for example: credible furans > 1.5ppm showing a clear upward trend or following the indications of a sister unit found to be severely aged when scrapped. and/or Indications of a worsening overheating fault.
100	Very advanced ageing for example: credible furans >2ppm with an upward trend or following the indications of a sister unit found to be severely aged when scrapped. and/or Serious overheating fault.

Table 7

Electrical test data may be used to support a higher thermal score where they show poor insulation condition. Electrical tests can provide further evidence to support the asset management plan for individual transformers e.g. where a significant number of oil tops ups have been required for a particularly leaky transformer and it is suspected that this is diluting the detectable Furans in the oil. However experience shows that not all poor thermal conditions can be detected by electrical tests which is why DGA data remains the focus for scoring the Thermal Condition Factor.

MECHANICAL CONDITION FACTOR (MCF)

Mechanical condition is assessed using Frequency Response Analysis (FRA) results.

Score	Mechanical Condition Factor (*MCF*)
0	No known problems following testing.
1	No information available.
3	Anomalous FRA results at the last measurement which are suspected to be a measurement problem and not an indication of mechanical damage. and/or Corrected loose clamping which may reoccur.
10	Loose clamping.
30	Suspected mechanical damage to windings. This does not include cases where the damage is confirmed.
60	Loose or damaged clamping likely to undermine the short circuit withstand strength of the transformer.
100	Confirmed mechanical damage to windings.

Table 8

Mechanical condition is assessed using Frequency Response Analysis (FRA) results; FRA is used to detect movement in the windings of the transformer, these data are supplemented by family history e.g. where post mortem analysis of a similar transformer has confirmed winding movement and DGA results (which indicate gas generation from loose clamping) as appropriate.

OTHER COMPONENT FACTOR (OCF)

The Other Components score uses an assessment of other aspects, this includes:

- **Tap-changers**. Tap-changers are maintained and repaired separately to the transformer and defects are most likely repairable therefore tap-changer condition does not normally contribute to the AHI score. Where there is a serious defect in the tap-changer and it cannot be economically repaired or replaced this will be captured here.

- **Oil Leaks.** During the condition assessment process transformers may be found to be in a poor external condition (e.g. severe oil leaks), this will be noted and the defect dealt with as part of the Asset Health process. The severity of oil leaks can be verified by oil top up data. Where there is a serious defect and it cannot be economically repaired, this will be captured here.

- Other conditions such as tank corrosion, excessive noise or vibration that cannot be economically repaired will be captured here.

Score	Other Component Factor (*OCF*)
0	No known problems.
10	Leaks (in excess of 2000 litres per annum) that cannot be economically repaired. and/or Tap-changer that is known to be obsolete and spare parts are difficult to acquire.
30	Exceptional cases of leaking (in excess of 10 000 litres per annum) that cannot be economically repaired where the annual oil top up volume is likely to be diluting diagnostic markers. and/or Other mechanical aspects potentially affecting operation that cannot be economically repaired for example: tank corrosion, excessive noise or vibration.
60	Exceptional cases of leaking (in excess of 15 000 litres per annum) that cannot be economically repaired and where the effectiveness of the secondary oil containment system is in doubt and would be difficult or impossible to repair without removing the transformer. and/or Tap-changer that is known to be in poor condition and obsolete with no spare parts available.
100	Confirmed serious defect in the tap-changer that cannot be economically repaired or replaced.

Table 9

UNDERGROUND CABLE PARAMETERS

SCORING PROCESS

The formula to determine the EOL modifier for cables, which is capped at a maximum of 100, is:

$$EOLmod = ACS + Sub\_ADJ$$

Equation 21

Where ACS is the main asset condition score and Sub_Adj is the sub-asset condition score adjustment.

$$ACS = AALc * GFI + DUTY + \max(DEFECTS,\ SEVERITY) + ACCESS + \max(OIL, PROIL) + Main\_ADJ$$

Equation 22

The factors defined in this formula are described as listed below.

CURRENT AGE VARIATION FROM ANTICIPATED ASSET LIFE AALC:

In the table below variation= age – anticipated asset life. The anticipated asset life is listed in the appendix section and reflects specific issues associated with a particular family.

Variation from anticipated asset life (*AALc*)	
>=Variation	Score
-100	0
-5	2
0	5
5	20
10	25
15	30

Table 10

ASSET SPECIFIC FAILURE MODES

Some assets are not able to be influenced by maintenance as detailed below.

GENERIC FAMILY ISSUE (GFI)

This component is used to score any known generic family issues which can affect the anticipated life of the asset, that is, a design weakness may become apparent for a particular family of assets. For example it has been determined that type 3 cables have a known generic defect. Type 3 cables are AEI and pre-1973 BICC oil filled cables with lead sheath and polyvinyl chloride (PVC) over sheath and an additional risk of tape corrosion or sheath failure. This scoring takes account of the family design issues which are a risk to the anticipated asset life.

Generic Family Issue (*GFI*)	
	Weighting
Evidence of design issue	3
Vulnerable to design issue	2
Vulnerability to design issue mitigated	1.5
Other	1

Table 11

DUTY (DUTY)

This represents the operational stress that a cable route has undergone during the last 5 years. It is measured in terms of the hours the cable has operated at or above its maximum designed rating during the last 5 years.

The England and Wales transmission owner will set this factor to zero, as cables are not operated at or even near maximum designed rating.

Duty – hours at or above max rating (*DUTY*)	
>= Hours	Score
0	0
24	5
48	10
120	15

Table 12

DEFECTS (DEFECTS)

This represents the total number of faults and defects raised against each asset over the last 10 complete financial years.

Number of Defects (DEFECTS)	
>= Number of Defects	Score
0	0
10	15
40	35
90	40

Table 13

SEVERITY (SEVERITY)

The severity of repairs to remedy faults and defects is quantified by the time spent carrying out these repairs.

Repair Time in Hours (SEVERITY)	
>= Time	Score
0	0
500	5
950	20
1500	30
2350	40

Table 14

DAYS NOT AVAILABLE OVER LAST YEAR PERIOD APRIL/APRIL (ACCESS)

Access (*ACCESS*)	
>= Days	Score
0	0
50	2
100	5
200	10
300	20

Table 15

HISTORICAL OIL LEAKS IN LAST 10 YEARS SCORE (OIL)

This is the litres of oil leaked in the last 10 years.

Oil leaks last ten years (*OIL*)	
>= Litres	Score
0	0
1000	5
1500	10
2000	15

Table 16

PRO-ROTA TO 1KM OIL LEAKS IN LAST 10 YEARS SCORE (PROIL)

This is the pro-rota to 1km litres of oil leaked in the last 10 years

Oil leaks last ten years (*PROIL*)	
>= Litres	Score
0	0
200	5
400	10
500	15

Table 17

MAIN CABLE INFORMATION (MAIN_ADJ)

The following condition scores will be applied when determining a cable EOL score. These factors tend to be bespoke to each cable route, so need to be included in the calculation as an adjustment component.

- Known presence of tape corrosion. (Score 10)
- Whether the cable circuit has been tagged with the Perfluorocarbon tracer gas (PFT) which enables the prompt and accurate location of oil leaks. (Score 5)

SUB-ASSET INFORMATION (SUB_ADJ)

The cable has a number of sub-asset upon which it is reliant for operation. These sub-assets also experience deterioration.

- Risk of failure of old style link boxes. (Score 5)
- Risk of stop joint failure. (Score 5)
- Risk of sheath voltage limiter (SVL) failure. (Score 5)
- Poor Condition of joint plumbs. Information about whether they have been reinforced. (Score 5)
- Known faults with oil tanks, oil lines, pressure gauges and alarms. (Score 5)
- Condition or faults with cooling system (if present). (Score 5)
- Occurrence of sheath fault (5) Multiple faults (10)
- Known issues with the cable's laying environment (Score 5)

OVERHEAD LINE CONDUCTOR PARAMETERS

SCORING PROCESS

Overhead Line Conductors are assigned an end of life modifier using a 2 stage calculation process. The first stage assesses each circuit section based on conductor type, time in operating environment and number of repairs. The second stage assesses information gathered from condition assessments. The overall end of life modifier is given by:

$$EOLmod = \begin{cases} PRE_{HS} & if\ VAL = 0 \\ SEC_{HS} & if\ VAL = 1 \end{cases}$$

Equation 23

Where:

PRE_{HS} is a 'Preliminary' or 'First Stage' score and

SEC_{HS} is a 'Secondary Stage' Score.

The maximum value of *EOLmod* is 100.

The preliminary health score PRE_{HS} is effectively capped at 70, which ensures that an asset is never replaced on the basis of only age and repair information alone. If we believe an asset to be in a worst condition than PRE_{HS} indicates then additional sampling would need to be performed on that asset.

The EOL modifier methodology in this section has been developed assuming an ideal situation where all data is available. However the methodology has been carefully designed to cope with situations where there are large gaps in our data, such that a meaningful score can still be generated.

PRELIMINARY STAGE

Each conductor is assigned to a 'family' which has an associated asset life. For ACSR conductors, this is based on:

a. Grease Type (Fully or Core-only greased). This can be derived from installation records and sampling of the conductor. This record is stored in our Ellipse Asset Inventory.

b. Conductor Type (e.g. Zebra or Lynx). This can be derived from installation records and sampling of the conductor. This record is stored in our Ellipse Asset Inventory.

c. Environment Category (A – 'Heavy Pollution', B – 'Some Pollution', C – 'No Pollution', d – 'Wind Exposed'. Sections may pass through different environments so the most onerous category experienced is assigned. This is based on mapping data and employs distance to the coast and polluting sources. Wind Exposed environments generally refer to heights above sea level of 150m (where high amplitude, low frequency 'conductor galloping' is more prevalent) as well as areas where wind induced oscillations have been observed by field staff.

AAAC/ACAR conductors are one family and have one asset life.

HTLS conductors are one family and have one asset life.

The preliminary end of life modifier is taken to be the maximum of an age based score and repair based score. If the repairs component of the equation is high it always requires further investigation, regardless of the age of the asset. The spread of repair locations is also significant. Clusters may appear on spans/ sections with local environment characteristics (e.g. turbulence level). For example, the damping or configuration of the conductor bundle may require intervention to prevent earlier failure of this part of the line.

Because the processes of corrosion, wear and fatigue reduce wire cross section and strength over time, 'Age' of a line in its respective operating environment is a significant part of the conductor assessment.

Our ability to detect all the condition states of a conductor is limited. This is a composite, linear asset where condition states remain hidden without intrusive analysis. The act of taking a sample is time consuming (average 3-4 days per line gang), can only be done in places where conductor can be lowered to the ground and introduces more risk to the system by the insertion of joints between new and old conductor. This means that a preliminary health score is needed to enable scores to be determined for assets that don't have sample data. This preliminary health score is necessarily based on factors such as family weighting, age and repairs, as these are the only sets of data known for all of our OHL conductor assets.

$$PRE_{HS} = W_{FAM} * \max(AGE, REP)AGE$$

$$AGE_{SCORE} = \begin{cases} 0 & AGE - AAL \leq -8 \text{ or } AGE \leq 5 \\ 35 & AGE - AAL \geq -3 \\ 2(AGE - AAL) + 41 & otherwise \end{cases}$$

$$REPAIR_{SCORE} = \begin{cases} 0 & REP = 0 \\ 45 & REP \geq 0.6 \\ 75(REP) & otherwise \end{cases}$$

Equation 24

REP= Number of conductor repairs in the span being assessed divided by the total number of spans on the route or section.

AGE=Reporting year – Installed year

AAL=Anticipated asset life of the family. This is obtained from the end of life FMEA end of curve for the family. Please see the failure modes section for a general explanation of how these curves are determined and what distribution is used.

Repairs range from a helical wrap of aluminium to a compression sleeve to the installation of new pieces of conductor (requiring joints) depending on damage severity. Within any given span, the most common areas of conductor repair on our network are at or adjacent to clamping positions, in particular spacers. On routes where the number of repairs is high, exposure to wind induced conductor motion is the common characteristic. This measure is an indication of the environmental input to a line, in particular wind exposure. It does not provide a complete picture, especially for latent processes of corrosion within a conductor and fretting fatigue that has not yet manifested in broken strands.

W_{FAM} is a family weighting score derived from OHL conductor sample data. The sample data is calculated according to the formula S_i in the following section. W_{FAM} ensures that the PRE_{HS} is a reasonable proxy for asset condition given the lack of actual sample data. W_{FAM} is capped inside a range from 1.0 to 2.0 to prevent PRE_{HS} from becoming too dominant. This means PRE_{HS} is effectively capped at 70.

$$W_{FAM} = \frac{Average\ Sample\ Score\ within\ family}{Average\ Sample\ Score\ across\ all\ OHL\ conductor\ assets}$$

Equation 25

VALIDITY MULTIPLIER

To aim for condition data that is indicative of the whole circuit or section being assessed, a validity criterion is applied. All environment categories the circuit passes through must be assessed and at least one conductor sample per 50km is required.

Results of the secondary health score are only considered if the criterion for a 'valid' set of condition assessments described above is met. Note that a zero value of VAL implies that there is not enough condition information and therefore the preliminary health score will be used.

$$VAL = Criteria\ A * Criteria\ B$$

Equation 26

Validity Criteria A	***Criteria A value***
No. of Environment Categories/No. of Categories Assessed = 1	1
No. of Environment Categories/No. of Categories Assessed <1	0
Validity Criteria B	***Criteria B value***
No. of samples per 50 route km >=0.02	1
No. of samples per 50 route km <0.02	0

Table 18

SECOND STAGE

On completion of the preliminary scoring, further condition indications will be reviewed to allow a second stage assessment of a conductor.

$$S_i = AH + VA + GL + DSS + GT + CL + DAS + TBL + TT$$

$$PCSI = \max_{All\ phase\ conductor\ samples}(S_1, S_2, S_3 \ldots S_n)$$

$$SEC_{HS} = max(PCSI, \quad COR)$$

Equation 27

The PCSI component is therefore determined by adding up the component scores for each phase conductor sample (S_i). This generates a total result for each phase conductor sample. The maximum total result across all phase conductor samples then gives the value if *PCSI*. This second stage assessment is the maximum of either *PCSI* or non-intrusive core corrosion surveys.

A phase conductor sample requires a conductor to be lowered to the ground, where typically, a length is taken from the anchor clamp to the first 'spacer clamp' in the span. The test is destructive, this is cut out and then a new piece of conductor jointed in. The spacer clamp area is a corrosion, wear and fatigue location where the worst conductor degradation is usually witnessed. Other locations of interest within a conductor span are the area around a suspension shoe, dampers, any other clamping device and the bottom of the wire catenary.

Phase Conductor Sampling Interpretation (out of 100)	$AH + VA + GL + DSS + GT + CL + DAS + TBL + TT$
Presence of Aluminium Hydroxide (a corrosion product) (*AH*) (0-15)	
Significant – Area/Areas with full surface coverage of powder.	15
Present – Area/Areas with small clusters of powder or a small number of particles scattered over surface	10
None	0
Visual Assessment of Steel Core Galvanising (*VA*) (0-15)	
Loss – 10% + galvanising is missing/damaged	15
Small Loss – small areas of (no more that 10% of damaged/ missing galvanising	10
Good – Galvanising appears intact	0
Grease Level and Quality (*GL*) (0-10)	
Core Only Greased Dry	10
Core Only Greased Flexible	5
Fully Greased Dry	2.5
Fully Greased Flexible	0
Diameter of Steel Strands (*DSS*) (0-5)	
Less than 0%, or lower than the Min Spec of 3.18mm	5
Between 0 and 0.4 % (inclusive) Min Spec of 3.18mm	2.5
Greater than 0.4 % Min Spec of 3.18mm	0
Measurement of Galvanising Thickness on Outer and Inner Face of Steel Core Wire (*GT*) (0-5)	
Average <20 microns	5
Average >=20 microns	2
Average >=49 microns	0
Measurement of Corrosion Layer of Outer and Inner Face of Aluminium Strands (*CL*) (0-5)	
Average >=275	5
Average >100	2
Average >0	0
Diameter of Aluminium Strands (*DAS*) (0-5)	
Average >=275	5
Average >100	2
Average >0	0
Average Tensile Breaking Load of Outer Aluminium Strands (*TBL*) (0-20)	
<1120N	20
>=1120N	15
>=1280N	10
>=1310N	0
Torsion Test (Average Revolutions to Failure of Outer Aluminium Strands (*TT*) (0-20)	
<1 revolution to failure	20
>=1 revolution to failure	15
>=10 revolutions to failure	5
>=18 revolutions to failure	0

Table 19

Eddy current non-intrusive core corrosion surveys measure the residual zinc coating of the steel core within ACSR. These employ a device that is required to be mounted on and propelled down a conductor wire. Changes in magnetic flux density detect loss of zinc and aluminium to the steel core.

Core Sample Interpretation	***Score (COR)***
Residual zinc coating of 5 microns or less (‘Severe Corrosion’)	50
Minimum	0

Table 20

OVERHEAD LINES FITTINGS PARAMETERS

Overhead Line Fittings are assigned a HS using a 3 stage calculation process. The first stage is preliminary assessment based on age. The second stage is a visual condition assessment (referred to as a ‘Level 1’) and the third stage is an ‘outage’ or intrusive condition assessment (‘Level 2’).

Scoring assessments are made on sections of circuit that are typically homogenous in conductor type, installation date and environment.

OHL FITTINGS FAILURE MODE GROUPING

OHL fitting assets are currently split into two different failure mode groups each of which has a different earliest and latest onset of failure value, and therefore a different AAL. These groupings are Quad Conductor Routes and Twin Conductor Routes.

OHL FITTINGS END OF LIFE MODIFIER

The formula to determine the EOL modifier of fittings is given below, and is capped at a maximum of 100.

$$EOLmod = \frac{\max(SPA, DAM, INS, PHF)}{6}$$

Equation 28

A maximum score of spacers, dampers, insulators and phase fittings is applied, since the probability of the asset failing is determined by the weakest component. In this case the weakest component is the component that has the highest EOL modifier component score.

The components of this formula will all be broken down and described in more detail below. The meaning of these components is:

1. Spacers (*SPA*)
2. Dampers (*DAM*)
3. Insulators (*INS*)
4. Phase Fittings (*PHF*). This category includes linkages (shackles, straps, dowel pins etc.) and Arcing Horns/Corona Rings.

This is then averaged out across a circuit for each component class (spacers, dampers, insulators and phase fittings), so it remains is necessary to review the results at the routelette/span level to understand the distribution of condition across the system. A targeted intervention may be required within a component class or within a sub section of the OHL circuit or both.

PRELIMINARY ASSESSMENT

The Preliminary assessment of spacers, dampers, insulators and phase fittings is based on the age of the oldest components versus the anticipated life. The preliminary score for each of these components (SPA_{PRE} , DAM_{PRE} , INS_{PRE} , PHS_{PRE}) can be determined from the table below.

$$PRELIMINARY\_SCORE = \begin{cases} 0 & AGE - AAL \leq -13 \\ 300 & AGE - AAL \geq -3 \\ 30(AGE - AAL) + 390 & otherwise \end{cases}$$

Equation 29

LEVEL 1 AND LEVEL 2 CONDITION ASSESSMENT

Each of the categories, spacers, dampers, insulators and phase fittings are assessed against condition statements. Each of these statements has a weighting which results in the overall End of Life modifier.

Level 1 is a visual condition assessment of fittings components. The usual method of data collection is by High Definition Camera mounted to a helicopter.

Level 2 is an 'outage' or 'intrusive' condition assessment. This extra degree of inspection is required on those components likely to produce 'false negative' or 'false positive' results when the level 1 approach is adopted. This includes wear to phase fittings and loss of dielectric strength in insulation. Only some of the components have level 2 information.

SPACERS

$$SPA = (SPA_{PRE} * LVL1) + SPA_{FAM} + SPA_{LVL1}$$

Equation 30

Where:

SPA is the overall spacer score

SPA_{PRE} is the preliminary spacer score

LVL1 is a multiplier: if Level 1 condition assessment is available (=0), if Level 1 condition assessment is not available (=1)

SPA_{FAM} is the spacer family score

SPA_{LVL1} is the Level 1 Condition Assessment score for spacers.

There is no Level 2 stage assessment for Spacers

Spacer Family SPA_{FAM}	**Score**
Phase Quad and Twin Semi-Flexible – Andre, BICC, Bowthorpe, Delta Enfield, Metalastik.	200
Phase Quad Semi-Flexible – Hydro Quebec.	0
Phase Quad and Triple Semi-Flexible, Key-Installed – PLP, Dulmison, Mosdorfer.	0
Phase Twin Rigid, Key-Installed – PLP, Dulmison, Mosdorfer.	0
Phase Quad, Twin and Triple Spacer Damper – PLP, Dulmison, Mosdorfer.	0
Jumper and Downlead Quad, Twin and Triple Rigid Spacers – Andre, Metalastik, PLP, TYCO, Bonded and Compression types.	0

Table 21

SPACER VISUAL CONDITION STATEMENTS SPA_{LVL1}

Spacer	Good Condition	Dull Appearance	Black Appearance	Slight Oxidation Deposits Around Conductor Clamp and Locking Pins	Severe Oxidation Deposits Around Conductor Clamp and Locking Pins
Tight and Secure	0	100	250	300	400
Locking Pins Ineffective or Loose	500	500	500	500	500
Rubber Missing	500	500	500	500	500
Loose Arms	500	500	500	500	500
Clamps Loose	500	500	500	500	500
Clamps Open	500	500	500	500	500
Missing	500	500	500	500	500

DAMPERS

$$DAM = (DAM_{PRE} * LVL1) + DAM_{LVL1}$$

Equation 31

Where:

DAM is the overall damper score

DAM_{PRE} is the preliminary damper score

LVL1 is a multiplier: if Level 1 condition assessment is available (=0), if Level 1 condition assessment is not available (=1)

DAM_{LVL1} is the Level 1 Condition Assessment score for dampers.

There is no Level 2 stage assessment for dampers.

DAMPER VISUAL CONDITION STATEMENTS DAM_{LVL1}

Damper	Galvanising Weathered, Dull Appearance	Galvanised Coating Starting to Deteriorate	Light Rust, Majority of Galvanised Coating Missing	Heavy Rust	Heavy Corrosion, Pitting of Steelwork and Some Section Loss
0-20° Droop	0	0	50	100	150
20°-40° Droop	0	0	50	150	200
40° + Droop	300	300	300	300	300
Bell(s) missing, messenger wire broken or slipped	300	300	300	300	300
Slipped	300	300	300	300	300
Missing	300	300	300	300	300

Table 22

INSULATORS

$$INS = (INS_{PRE} * LVL1) + (INS_{FAM} * LVL2) + (\max(INS_{LVL1}, INS_{LVL2}))$$

Equation 32

Where:

INS is the overall insulator score

INS_{PRE} is the preliminary insulator score

LVL1 is a multiplier: if Level 1 condition assessment is available (=0), if Level 1 condition assessment is not available (=1)

INS_{FAM} is the Insulator Family Score

$LVL2$ is a multiplier: if Level 2 condition assessment is available (=0), if Level 2 condition assessment is not available (=1)

INS_{LVL1} is the Level 1 Condition Assessment score for insulators.

INS_{LVL2} is the Level 2 Condition Assessment score for insulators.

Insulator Family INS_{FAM}	**Score**
Porcelain	0
Grey Porcelain without zinc collars	100
Brown Porcelain without zinc collars	200
Glass	0
Polymeric	0

Table 23

Insulator Level 2 Condition Assessment INS_{LVL2}	**Score**
No units failed 1kV resistance test (only applies to porcelain insulation)	0
Evidence of no more than 1-2 units in a string failed 1kV resistance test. (only applies to porcelain insulation)	200
Evidence of cracking/crazing detected through use of corona camera (this is new equipment). (only applies to porcelain insulation)	300
Evidence of 3 or more units in a string failed 1kV resistance test. (only applies to porcelain insulation) 40% loss of cross section of steel connecting pin (190kN) 10% loss of cross section of steel connecting pin (300kN)	300
Evidence of multiple strings with 3 or more units in a string failed 1kV resistance test (only applies to porcelain insulation)	500

Table 24

INSULATOR FAMILY INS_{FAM}

Insulator	Galvanising Weathered, Dull Appearance	Galvanised Coating Starting to Deteriorate	Light Rust on Bells, Majority of Galvanised Coating Missing	Heavy Rust on Bells	Bells Severely Corroded and Some Section Loss
No Pollution	0	50	50	100	100
Evidence of Light Pollution	50	100	100	100	150
Evidence of Heavy Pollution	100	100	100	100	150
Visible Burn Marks	150	150	250	250	250
Evidence of Crazing	300	300	300	300	300

Table 25

PHASE FITTINGS

$$PHF = (PHF_{PRE} * LVL1) + PHF_{LVL1}$$

Equation 33

Where:

PHF is the overall phase fittings score

PHF_{PRE} is the preliminary phase fittings score

LVL1 is a multiplier: if Level 1 condition assessment is available (=0), if Level 1 condition assessment is not available (=1)

PHF_{LVL1} is the Level 1 Condition Assessment score for phase fittings.

Phase Fittings are made up of

1. Suspension Linkages: Shackle, Ball Ended Eye Link, Yoke Plate, Shoes, Maintenance Bracket, Weights, Straps. (LNK_{SUS})
2. Tension Linkages: Landing Pin, Shackle, Ball Ended Eye Link, Straps, Yoke Plate. (LNK_{TEN})
3. Arcing Horns and Corona Rings. (*ARC*)
4. Dowel Pins and Bolts. (*DOW*)

$$PHF_{LVL1} = \max((max(LNK_{SUS})), (max(LNK_{TEN})), ARC, DOW)$$

Equation 34

The $max(LNK_{SUS})$ means maximum of all suspicion leakages in the route. $Max(LNK_{TEN})$ means maximum of all tension linkages in the route.

These have their own set of condition statements and scores as set out below.

PHF_{LVL1} SUSPENSION AND TENSION LINKAGES

Phase and Earthwire Fittings (Suspension & Tension)	Galvanising Weathered, Dull Appearance	Galvanised Coating Starting to Deteriorate	Light Rust, Majority of Galvanised Coating Missing	Heavy Rust	Heavy Corrosion, Pitting of Steelwork and Some Section Loss
Minimal Wear 0-10%	0	100	200	200	300
Slight Wear 10-20%	100	200	200	300	400
Moderate Wear 20-40%	200	200	300	400	400
Heavy Wear 40-60%	300	300	400	500	500
Severe Wear >60%	500	500	500	500	500

Table 26

PHF_{LVL1} ARCING HORNS AND CORONA RINGS

Arcing Horn/ Corona Ring	Galvanising Weathered, Dull Appearance	Galvanised Coating Starting to Deteriorate	Light Rust, Majority of Galvanised Coating Missing	Heavy Rust	Heavy Corrosion, Pitting of Steelwork and Some Section Loss
Tight and Secure	0	100	200	300	400
Missing Components, Locking Nuts etc	200	300	300	300	400
Loose	300	300	400	400	400
Missing	500	500	500	500	500
Incorrect Length	500	500	500	500	500

Table 27

PHF_{LVL1} DOWEL PINS AND BOLTS

Dowel Pin/ Bolts	Galvanising Weathered, Dull Appearance	Galvanised Coating Starting to Deteriorate	Light Rust, Majority of Galvanised Coating Missing	Heavy Rust	Heavy Corrosion, Pitting of Steelwork and Some Section Loss
Minimal Wear 0-10%	0	100	200	200	300
Slight Wear 10-20%	100	200	200	300	400
Moderate Wear 20-40%	200	200	300	400	400
Heavy Wear 40-60%	300	300	400	500	500
Severe Wear >60%	500	500	500	500	500
Missing	500	500	500	500	500

Table 28

OVERALL END OF LIFE MODIFIER FOR OHL FITTINGS

The end of life modifier formula for fittings given at the beginning of this section is reproduced below with a mathematic summary of how each component is determined.

$$\boldsymbol{EOLmod} = \mathbf{max}(\boldsymbol{SPA}, \boldsymbol{DAM}, \boldsymbol{INS}, \boldsymbol{PHF})$$

Equation 35

Where:

$$SPA = (SPA_{PRE} * LVL1) + SPA_{FAM} + SPA_{LVL1}$$

$$DAM = (DAM_{PRE} * LVL1) + DAM_{LVL1}$$

$$INS = (INS_{PRE} * LVL1) + (INS_{FAM} * LVL2) + (\max(INS_{LVL1}, INS_{LVL2}))$$

$$PHF = (PHF_{PRE} * LVL1) + PHF_{LVL1}$$

$$PHF_{LVL1} = \max((max(LNK_{SUS})), (max(LNK_{TEN})), ARC, DOW)$$

IMPLEMENTATION PLAN

DATA COLLECTION FOR EOL MODIFIER PARAMETERS

The data collection plan for each asset type is described in the table below. This table indicates the input, for which data needs to be collected, and the plan to populate this input.

Asset	Input Parameter	Data Collection Plan
Circuit Breakers	Age	This is known and is calculated from installation date
Circuit Breakers	Deterioration Groupings	Groupings known, additional work is ongoing to finanlise actual groupings.
Circuit Breakers	AAL	This quanity is calculated from ealiest and latest onset values applicable to each deterioration group
Circuit Breakers	OC	This data can be extracted from our internal system.
Circuit Breakers	MOC	This data can be extracted from our internal system.
Circuit Breakers	FC	This data can be extracted from our internal system.
Circuit Breakers	MFC	This data can be extracted from our internal system.
Circuit Breakers	SF6 leakage kgs	SF6 leakage is reported annually, so this dataset can be utilised for calculating the NOMs health score
Circuit Breakers	SF6 inventory	SF6 leakage is reported annually, so this dataset can be utilised for calculating the NOMs health score
Transformers/Reactors	Oil sample data	Received annually
Transformers/Reactors	FRA data	Received several times during lifetime of transformer
Transformers/Reactors	Leakage data	This data can be extracted from our internal system.
Transformers/Reactors	Visual assessments	Refreshed annually
Transformers/Reactors	DCF	Data already available for 2016/17. Refreshed annually using above data.
Transformers/Reactors	TCF	Data already available for 2016/17. Refreshed annually using above data.
Transformers/Reactors	MCF	Data already available for 2016/17. Refreshed annually using above data.
Cables	Age	This is known and is calculated from installation date
Cables	Deterioration Groupings	Groupings already known
Cables	AAL	This quanity is calculated from ealiest and latest onset values applicable to each deterioration group
Cables	GFI	Work is ongoing to categorise each asset into a general family group.
Cables	DEFECTS	This data can be extracted from our internal system.
Cables	SEVERITY	This data can be extracted from our internal system.
Cables	ACCESS (days not available)	Average circuit unreliability is reported annually. This dataset can be used as the basis for populating this score
Cables	OIL	Data already available
Cables	PROIL	Data already available
Cables	Adjustments	Exercise to work through each cable asset and assign adjustments
OHL conductors	Age	This is known and is calculated from installation date
OHL conductors	Deterioration Groupings	Groupings already known
OHL conductors	AAL	This quanity is calculated from ealiest and latest onset values applicable to each deterioration group
OHL conductors	Repairs	Extracted from internal system
OHL conductors	S_i	Currently implementing plan to take more conductor samples, which will improve accuracy of scores
OHL conductors	COR	Currently implementing plan to carry out further corrosion surveys
OHL fittings	Age	This is known and is calculated from installation date
OHL fittings	Deterioration Groupings	Groupings already known
OHL fittings	AAL	This quanity is calculated from ealiest and latest onset values applicable to each deterioration group
OHL fittings	Family Score	Data already available
OHL fittings	Lvl1 Score	Currently implementing plan to take gather more Level1 condition scores
OHL fittings	Lvl2 Score	Some data already available. Plan to collect further data

Table 29

ASSUMPTIONS

The table below outlines the NGET assumptions for parameters in the Common Methodology or in this Process Appendix. Where applicable, a high level description has been given for the plan to reduce or eliminate, reduce limitations or biases implied by the assumption.

No	Section	Parameter affected	Assumptions	Plan to reduce or eliminate
1	End of Life Modifier	EOL conditional probability of failure	Assume all end of life failure curves follow the Weibull distribution given by earliest and latest onset of failure.	Review during testing, validation and calibration
2	End of Life Modifier	EOL conditional probability of failure	An asset is in a state requiring replacement when the conditional probability of failure has reached a level of 10%	Review during testing, validation and calibration
3	End of Life Modifier	Transformer and Reactor EOL modifier	Other Components Factor (OCF) set to zero due to data unavailability	For each transformer asset determine a score for this term and review during testing, validation and calibration
4	End of Life Modifier	all EOL modifiers	The age of an asset is given by current year-installation year. Where installation year is uncertain an estimate of the likely year is determined from available data.	
5	End of Life Modifier	all EOL modifiers	When data is not available then the affected component of EOL modifier is set to zero.	Review during testing, validation and calibration
6	End of Life Modifier	Transformers/Reactors	When preparing older datasets an assumption is made that component values for mechanic, thermal, dielectric are reasonably consistent with scoring categories proposed in this document in order to allow for a comparison.	Review during testing, validation and calibration
7	End of Life Modifier	Transformers/Reactors	Dielectric, thermal, mechanical and other component factors that compose the transformer EOL modifier are	Review during testing, validation and calibration

			independent of each other.	
8	End of Life Modifier	Transformers/Reactors	EOL modifier, and subsequent PoF, can be determined from using discrete scores	Review during testing, validation and calibration
9	End of Life Modifier	Transformers/Reactors	There is repeatability in the scores generated any given transformer from known condition information and data	Review during testing, validation and calibration
10	End of Life Modifier	Cables	Taking the maximum of defects and severity gives the most accurate view of PoF	
11	End of Life Modifier	Cables	The Generic Family Issues value can be represented by a single value that multiplies the AAL score	
12	End of Life Modifier	Cables	Duty score is set to zero	Consider estimating values and review during testing, validation and calibration process
13	End of Life Modifier	Cables	EOL modifier, and subsequent PoF, can be determined using a discrete scoring process	Review during testing, validation and calibration
14	End of Life Modifier	OHL conductors	EOL modifier can accurately be represented by age, AAL and number of repairs when actual condition information is not available.	Condition data is being collected from more OHL conductors to address this
15	End of Life Modifier	OHL conductors	The family weighting can be represented by a single value derived from sample results from OHL conductor assets of the same asset family type.	These family weightings will improve as more sample data is collected
16	End of Life Modifier	OHL conductors	The individual conductor sample result is represented by a single number determined by summing the underlying sample values.	Review during testing, validation and calibration
17	End of Life Modifier	OHL conductors	The overall OHL sample result can be determine as a single number determined by the maximum of the	Review during testing, validation and calibration

			individual conductor samples and corrosion survey.	
18	End of Life Modifier	OHL fittings	EOL modifier can accurately be represented by age when actual condition information is not available.	There is ongoing work to complete a Level 1 visual inspection for all fittings, which should mean we don’t need to use the Preliminary multiplier here
19	End of Life Modifier	OHL fittings and OHL conductors	EOL modifier, and subsequent PoF, can be determined from using discrete scores	Review during testing, validation and calibration
20	End of Life Modifier	OHL fittings	When the level 2 condition assessment score is unknown, the family score can be used as a proxy.	Review during testing, validation and calibration
21	End of Life Modifier	Circuit Beaker	The maximum of AGE FACTOR, DUTY_FACTOR, and SF6 FACTOR gives an reasonable representation of EOL modifier and therefore PoF. The weakest link in the chain is identified through taking the maximum of these values.	Review during testing, validation and calibration
22	End of Life Modifier	Circuit Beaker	The AGE _FACTOR and DUTY_FACTOR utilise a family specific deterioration value. Assume this can be represented by a single value for a given age/duty.	Review during testing, validation and calibration
23	End of Life Modifier	Circuit Beaker	The SF6 factor can be realistically represented through discrete scoring.	Review during testing, validation and calibration
24	End of Life Modifier	Circuit Beaker	Assume SF6 only becomes material to EOL modifer once high leakage thresholds are reached.	Review during testing, validation and calibration
25	Non-EOL	Circuit Breaker - Max Ops Limit (Operations)	The time since last intervention will be scaled up linearily by a single value based on number of operations exceeding maximum allowable operations.	

26	Non-EOL	Circuit Breaker - Rated Ops Limit (Operations)	The time since last intervention will be scaled up linearily based on number of operations exceeding maximum allowable operations.	
27	Non-EOL	Circuit Breaker - Op Tests	The probability of an event is reduced by a pre-defined percentage value when a remedial inspection is scheduled to take place.	Review during testing, validation and calibration
28	Non-EOL	Tap Changers - Intermediate and Major Ops Limits (Operations)	The time since last intervention will be scaled up linearily by a single value based on number of operations exceeding maximum allowable operations.	
29	FMEA	PoF	Asset failures are independent of other assets	
30	FMEA	PoF	Failure modes are independent	Review during testing, validation and calibration process.
31	FMEA	PoF	Assets can be grouped into similar categories that share similar charactistics	Refine groupings to improve agreement between model and expected events
32	FMEA	PoF	Only failure modes and consequences that are materially significant are considered	Review against faults, failures, defects in testing, validation and calibration phase to assess materiality
33	FMEA	PoF	Each asset can be modelled with one end of life failure mode representing failure due to wear-out that can't be addressed through maintenance interventions, and multiple non-end of life failure modes that can be addressed through maintenance interventions.	Review during testing, validation and calibration process
34	FMEA	P(Event)	Event groupings are structured to form a hierarchy of expected events e.g. a transformer fire also includes asset replacement, possible tank breach, trip and	Review during testing, validation and calibration process

			alarm.	
35	FMEA	PoF	The asset groups are assessed in isolation.	As further asset groups are included within FMEA, the interactions between all assets groups will be reflected in the risk score.
36	FMEA	PoF	The FMEA ealiest and latest onset parameters assume that the protection system designed to protect the asset are operational and functioning as expected	As further asset groups are included within FMEA, i.e. protection, the interactions between assets groups will be reflected in the risk score.
37	FMEA	PoF	Assume that when an intervention is carried out, that all tasks associated with that intervention are successfully completed	Review whether failure modes may be affected by maintenance tasks that might be deferrable.
38	FMEA	PoF	Non-end-of life FMs ignore impact of operational restrictions	Determine whether this is material and then whether to include these in a further iteration of FMEA
39	FMEA	PoF	The model parameters can be tuned through calibration against expected number of events	Review during testing, validation and calibration process
40	FMEA	PoF	Time based failure modes: PoF curves are defined by Weibull curves with two values - ealiest and latest onset of failure values for each failure mode. Assume these can be determined based TO experience using all available information: manufacturer information, understanding of asset design, innovation project results, failure investigation reports, failure, faults and defects data, forensics results, evidence from interventions, reviews of intervention policy, information from other network operators	Review against faults, failures, defects in testing, validation and calibration phase to understand that PoF matches expected number of events

			(international)	
41	FMEA	PoF	Duty-based failure modes: Assume this can be determined based TO experience using all available information: manufacturer information, understanding of asset design, innovation project results, failure investigation reports, failure, faults and defects data, forensics results, evidence from interventions, reviews of intervention policy, information from other network operators (international). See Non-EOL modifiers workstream parameters for treatment of max operations limits for those assets to which this FM applies	Review against faults, failures, defects in testing, validation and calibration phase to understand that PoF matches expected number of events
42	FMEA	PoF	Random failure modes: a constant failure rate represented by a single number. Assume this can be determined based TO experience using all available information: manufacturer information, understanding of asset design, innovation project results, failure investigation reports, failure, faults and defects data, forensics results, evidence from interventions, reviews of intervention policy, information from other	Review against faults, failures, defects in testing, validation and calibration phase to understand that PoF matches expected number of events

			network operators (international)	
43	FMEA	PoF/P(Event)	Two types of detection considered in risk model. Either detect worsening condition before failure occurs, or detect failed state before event occurs as result of failed state.	Review during testing, validation and calibration process
44	FMEA	PoF/P(Event)	Assume that specific failure modes on some asset types will only materialise under particular operating conditions e.g. circuit breaker interruptors once in a failed state will result in an event when required to operate to break load current. Assume that an inspection can detect this failure before it materialises as an event.	Review during testing, validation and calibration process
45	System Consequence	X	Methodology only considers the loss of customers who are disconnected by the least number of circuits which includes the asset in question (X=Xmin)	Areas where it is suspected that this assumption leads to significant error could be examined and the customer disconnection events considered be extended beyond X=Xmin
46	System Consequence	M_N	The equation for M_N assumes that the quantity and importance of customers lost at each site within the lost area are equal	Example areas could be tested with explicit calculation of all loss events vs the method used to test validity of assumption
47	System Consequence	P_I	Both potential values of P_I assume that circuit capacities are designed to SQSS requirements with no additional spare capacity	A survey of circuit capacities vs design requirements could potentially modify the values of P_I to take into account any average spare capacity

48	System Consequence	P_{oc}	The probability of disconnection is independent of the duration of asset unavailability due to the failure mode. It is assumed that if customer disconnection does not occur at the inception of the fault, it will not occur later.	P_f could be modified to include a term that involves D_f
49	System Consequence	P_{oc}	The probability of disconnection is independent of the health of assets neighbouring the asset in question. Often neighbouring assets will be of similar condition and health to the asset in question	P_f could be modified to include a term that involves the health of the asset
50	System Consequence	D	Disconnection duration is calculated by the minimum of all the mean restoration times of the events that have lead to the disconnection. The restoration time will in reality be of a function that is a composite of all the individual event restoration time functions.	Data could be gathered to construct the individual event restoration times. The probabilisitic function for minimum restoration could then be created and the mean of that function taken
51	System Consequence	VOLL	VOLL is assumed to be constant across GB except where Vital Infrastructure is connected.	If more research on locational VOLL was available then this data could be incorportated in the model
52	System Consequence	C_n	It is assumed that the boundary transfer impact of each circuit that is material to a boundary is comparable.	If boundary impacts of each circuit were calculated by the SO the costs could be scaled accordingly
53	System Consequence	C_n	It is assumed that asset failures are equally likely accorss the year	If data on the seasonality of a failure mode and the seasonality of boundary costs were available then each season could be treated separately
54	System Consequence	P_Y	The probability of coincident faults is independent of the health of assets	P_Y could be modified to include a term that involves the health of the asset

			neighbouring the asset in question. Often neighbouring assets will be of similar condition and health to the asset in question	
55	System Consequence	R_{RC}	It is assumed that alternative voltage support can be obtained through the ancillary services when compensation assets are unavailable. In reality this is sometimes not the case.	If research on the cost impacts of overvoltage on TOs and customers were available these could be included in the model
56	System Consequence	R_{RC}	It is assumed that the full capacity of a compensation asset is purchased when it is unavailable	If the SO could provide data on the relationship between asset availability and SO costs this could be incorporated
57	System Consequence	C_{MVArh}	It is assumed that the cost to procure MVArh across the network is equal	If the SO could provide locational cost data this could be incorporated
58	Safety Consequence	Probability of injury	The probability of injury is assessed on a per person basis, i.e. one individual. The probabilities add up to 1.	Review during testing, validation and calibration process
59	Safety Consequence	Probability of injury	Probabilities assume an individual within the vicinity of the asset when event occurs. The vicinity of an asset is 50m as described in TGN 227	Review during testing, validation and calibration process
60	Safety Consequence	Civil Fines	Mean value used for civil damage results; enough information from reference book to normally distribute fines	Review during testing, validation and calibration process
61	Safety Consequence	Probability of injury	Probability values based on expert opinion.	Review and refine during testing, validation and calibration process as data becomes available
62	Safety Consequence	Probability of injury	Assume 0.5m wide person, 2m tall	Review during testing, validation and calibration process

63	Safety Consequence	Probability of injury	For probability of injury for a category 4 - possibility of fatality event. Use calculations from a high pressure bushing disruptive failure. Full text in Knock C., Horsfall I, and Champion S.M (2013). *Development of a computer model to prefict risks from an electrical bushing failure.* Elsevier. This includes a spreadsheet of research carried out by Cranfield University, analysing the probability of fatality, being lacerated/penetrated by shrapnel with permanent injury (Major), and being lacerated/penetrated by shrapnel with no sustained injury (LTI). The analysis averaged (mean) their values across the different 'zones' for a vertical bushing, which related to the areas around a bushing ie directly in front, to the side etc, and averaging (mean) their values for a person at 15m,25m,35m,45m,and 55m.	Review during testing, validation and calibration process
64	Safety Consequence	Probability of injury	Probability of injury attributed to maximum injury sustained	Review during testing, validation and calibration process
65	Environment Consequence	Probability of environmental impact	Expert opinion used to create values	Review during testing, validation and calibration process
66	Environment Consequence	Probability of environmental impact	Probability of environmental impact relates to maximum impact occurred	Review during testing, validation and calibration process
67	Environment Consequence	Probability of environmental impact	Category 3 based on CB failures - majority of gas CB failures have resulted in category 1 (major) SF6 loss	

68	Environment Consequence	Probability of environmental impact	All CB probabilities of environmental impact based on gas CBs	
69	Environment Consequence	Probability of environmental impact	All cable probabilities of environmental impact based on oil-filled cables	
70	Safety and Environment Consequence	Exposure score	Logarithmic progression for exposure scores used to appropriately convert existing exposure criticalities for sites	Review during testing, validation and calibration process
71	Safety and Environment Consequence	Exposure score	Exposure scores are a weighting, the same matrix is used for both safety and environment criticalities	Review during testing, validation and calibration process
72	Financial	Cost of intervention	Financial cost of intervention including replacement is based on an averaged value determined for each asset.	Review during testing, validation and calibration process
73	Financial	Cost of intervention	The cost value is not flexed based on underlying specifications of the asset or the location of the asset.	Review during testing, validation and calibration process
74	Target Setting	Transformer and Reactor EOL modifier score	2010 values for mechanic, thermal, dielectric are consistent with updated NOMs methodolgy	Review during testing, validation and calibration process
75	Target Setting	All EOL modifier scores	Where health score cannot be calculated, use previous AHI to estimate a value. Typically less than 2% of assets affected by this assumption.	Review during testing, validation and calibration process
76	Target Setting	Cable EOL modifier	No Adjustment applied	Review during testing, validation and calibration process
77	Target Setting	Circuit Breaker EOL modifier	Current age=installation year-report year	Review during testing, validation and calibration process
78	Target Setting	Circuit Breaker EOL modifier	Deterioration groups based on reporting year	Review during testing, validation and calibration process

79	Target Setting	Circuit Breaker EOL modifier	No SF6 data or fault current data available for 2010 asset data. These factors are currently set to zero.	Consider estimating values and review during testing, validation and calibration process. Consider refinement for future.
80	Target Setting	All EOL modifier scores	Where data is not available then the affected component is currently set to zero	Consider estimating values and review during testing, validation and calibration process. Consider refinement for future.
81	Target Setting	OHL fittings	No 2010 OHL fittings data due to sample data availability/consistency with new method	Consider estimating values and review during testing, validation and calibration process. Consider refinement for future.
82	Target Setting	All PoF	2010 EOL modifier to PoF mapping function parameters are the same as 2016	Review during testing, validation and calibration process
83	Target Setting	Interventions - All Assets	Applying NLR replacement dates from the NOMs submission in the reporting year	
84	Target Setting	All Assets	2016 asset inventory from 2016 RRP (NLR), 2010 asset inventory from March 2012 RIIO submission, which was frozen at Nov 2010	
85	Uncertainty	Confidence Interval	Estimating the CI of MC trials of a single risk methodolgy (as defined in the document) is sufficient to generate reliable estimates of uncertainty.	As part of testing, validation and calibration alternative formulations for generating Risk maybe developed and the spread of results across many methods used to assess the level of uncertainty.

UNCERTAINTY (4.3.)

REQUIREMENTS

In line with the Direction and the recent feedback, NGET are required to explain how uncertainty will be accounted for, explaining any necessary adjustments, and providing assurance on suitability of final output values.

This methodology will address the above and provide further detail how uncertainty is quantified and treated at each of the following three stages:

1. Input uncertainty,
2. Process uncertainty,
3. Output uncertainty.

Specifically, it will address the following points:

1. How inputs that are not normally distributed will be treated.
2. How uncertainty introduced by data gaps will be estimated. (addressed in the FMEA/EOL modifier section)
3. How age of data inputs will be taken into account (e.g. time since last inspection). (addressed in the FMEA/EOL modifier section)
4. How estimates of output uncertainty are derived when the process equations cannot be broken down into combinations of analytically solvable equations.

MODEL DEVELOPED TO SPECIFICALLY ADDRESS REQUIREMENTS

The model combines results from MC simulation and analytical techniques to estimate the uncertainty in monetised network risk with confidence intervals. Monte Carlo simulation is used to calculate the uncertainty due to :

- non-normally distributed input parameters or,
- equations which we are unable to solve analytically
- The range of outputs for a fixed set of parameters

By turning on or off distributions for particular inputs, the sensitivity of the model to specific inputs can be assessed. The values for monetised events are normally distributed, as are the expected number of events generated via MC simulation. These are combined analytically to generate monetised network risk with CIs providing an estimate of uncertainty.

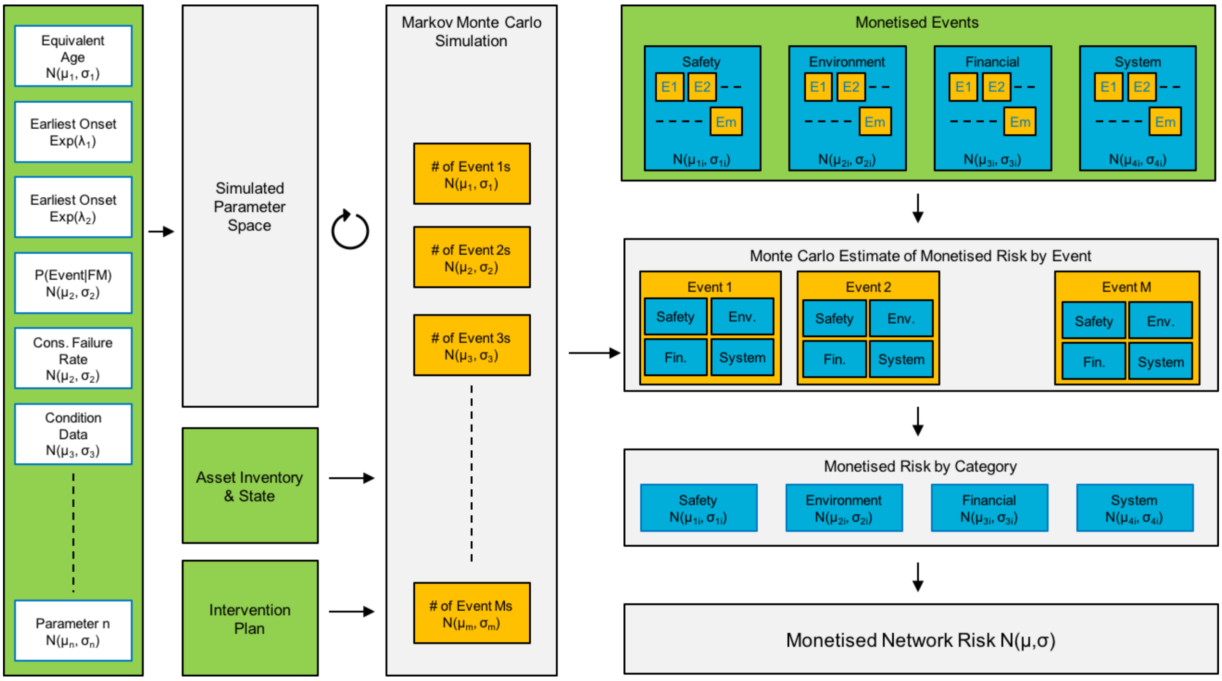


Figure 14

MONTE CARLO SIMULATION IS USED TO GENERATE CIS FOR THE EXPECTED NUMBER OF EVENTS

Mean values for parameters and distributions are provided to the model (how these are generated for the EOL modifier is explained in section 0)

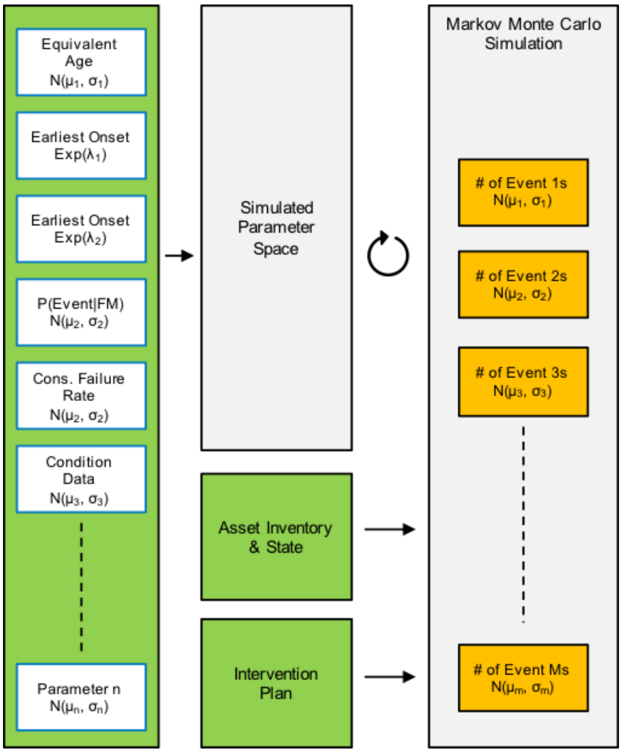


Figure 15

These are used to generate a parameter space containing values for each, centred around its mean and distributed according to the supplied parametric distribution.

For each MC trial a complete set of parameters is selected with replacement and used by the model to generate the expected number of each event for each year.

The results of many MC trials are used to generate a mean value for the expected number of events.

By the Central Limit Theorem, this mean is normally distributed irrespective of the distributions for generating parameters or calculating probabilities. This is used to generate CIs for the number of each Event.

ANALYTICAL TECHNIQUES AND MONTE CARLO ARE USED TO GENERATE NETWORK RISK WITH CIS

A second model generates MC estimates for Monetised Risk by Event type across the network and by Asset Type

The results of many MC trials are used to generate a mean value for the monetised risk by Event.

Again, by the Central Limit Theorem, this mean is normally distributed.

Letting NR denote Monetised Network Risk, then:

$$\boldsymbol{NR\ with\ CI = NR \pm 1.96 \times \sigma_{MNR}}$$

$where$:

$$\sigma_{MNR} = the\ std.deviation\ for\ the\ mean\ monetised\ risk$$

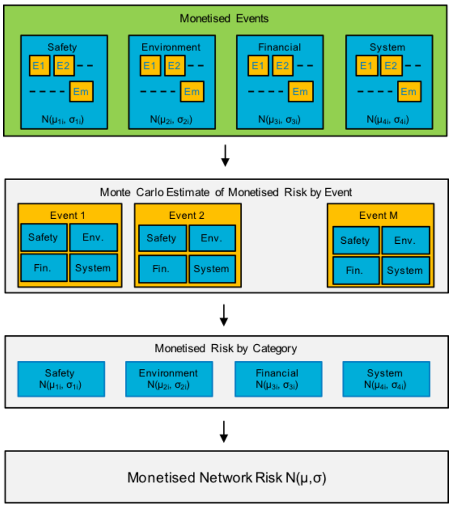


Figure 16

ESTIMATING UNCERTAINTY IN INPUT DATA - EOL MODIFIER

The following method can be used to estimate uncertainty in the EOL modifier value for each of the lead asset types described within the methodology. The steps for determining uncertainty are listed below, along with a worked example in italics. The worked example is for the case of a circuit breaker, but the principle can be readily translated to other asset types.

The principle is based on the approach illustrated in the diagram below. The lower the data quality is, the higher the uncertainty in the value of EOL modifier. Point A in the diagram represents an estimate of EOL modifier when all data is available, and therefore has the highest data quality and lowest uncertainty. Point C represents an estimate of EOL modifier when only age is available, and therefore has the lowest data quality and highest uncertainty. The percentage uncertainty shown in the figure is determined from the aggregated standard deviations associated with each element of missing data, as well as the standard deviation of the data when all data components are available.

Each of the points in the figure below represents uncertainty at a discrete level of data quality. A series of calculation stages are described in this methodology. Stage A involves estimating the standard deviation at different input data quality levels. This stage produces a standard deviation σ_A associated with missing each constituent data input of EOL modifier. Stage B involves estimating uncertainty of the EOL modifier when all data is available, which requires knowledge of the true value of EOL modifier. We call the standard deviation from the true value when all data is available σ_B. Stage C calculates the uncertainty by combining the standard deviations from stages A and B.

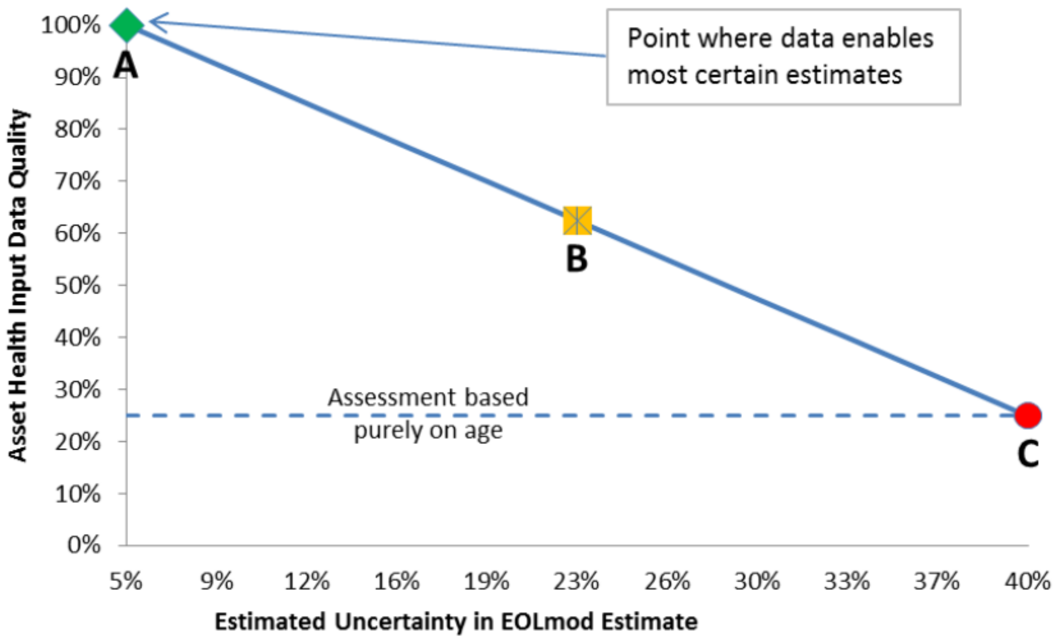


Figure 17

STAGE A

- First, identify the inputs that constitute the formula for EOL modifier for the specific lead asset type under investigation. At this stage, the analysis needs to consider all input data factors including those that may rarely be available (e.g. invasive condition assessments) to those that should always be available (e.g. age).
- Input factors relevant for switchgear:

  1) SF6

  2) Operational Duty

  3) Accumulated Fault current

  4) Age

The EOL modifier score is first calculated using all data. This quantity is called E_1.

The EOL modifier score is calculated again using one less data item (e.g. this could be SF6 data is removed) and is called E_2.

The standard deviation in the range of end of life modifiers when SF6 data is removed can then be calculated. The subscript i represents each asset. N is the total number of assets being considered in this calculation:

$$\sigma_{SF6} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(E_{1i} - E_{2i})^2}$$

Equation 36

A similar standard deviation calculation is then performed for each of the constituent data inputs of EOL modifier. This results in a known standard deviation associated with missing each element of the data: σ_{SF6}, $\sigma_{Operational\_Duty}$, $\sigma_{Accumulated\_Fault\_Current}$, and σ_{Age}

STAGE B

The minimum uncertainty needs to be quantified. This needs to consider both the true value of EOL modifier and the value calculated when all data is available.

This involves using scrapped and decommissioned asset reports to estimate the actual EOL modifier value at the time the asset was scrapped. In most cases these assets will have a true EOL modifier of 100, as the assets are usually decommissioned due to poor condition – this quantity is called E_T. The EOL modifier will be calculated at point just before decommissioning using all data considered within the methodology – this is called E_1. The indices i in the formula below represents each asset, and N is the total number of assets.

$$\sigma_{min} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(E_{Ti} - E_{1i})^2}$$

Equation 37

STAGE C

For each of the standard deviations calculated in stages A and B we need to determine the corresponding standard error. N is the number of assets that was used to calculate σ .

$$SE = \sigma / \sqrt{N}$$

Equation 38

APPLYING THE METHODOLOGY

Once the above calculations have been performed for a lead asset type in a reporting year then the uncertainty of every end of life modifier score can then be estimated. This is achieved by summing the uncertainty component standard error values according to the following formula. The overall standard error for a particular asset type is then given by:

$$SE_{overall} = \sqrt{\sum_{i}^{\substack{uncertainty \\ components}} SE_i^2}$$

Equation 39

where i represents each component of the standard error calculation for a particular asset

For example for a circuit breaker EOL modifier that is missing SF6 and operational duty data the overall standard error would be calculated as follows.

$$SE_{overall} = \sqrt{SE_{min}^2 + SE_{SF6}^2 + SE_{Operational\_Duty}^2}$$

Equation 40

The percentage uncertainty corresponding to a 95% upper and lower limit around EOL modifier is then given by:

$$U_2 = \pm \frac{1.96 * SE_2}{EOL\_mod} \%$$

Equation 41

Where EOL_mod is the end of life modifier for which we are estimating the uncertainty.

RISK TRADING MODEL

REQUIREMENTS

According to the Ofgem direction document and the recent feedback concerning a Risk Trading Model the key requirements are:

1. Demonstrates the benefit of any trade-off between incremental cost of doing or failing to do work and incremental movements in risk.

2. Demonstrating why and how investments are prioritised providing specific detail related to Licensees assets, past and future interventions, and work programmes

3. Reflect the description of processes and calculations described in the Common Methodology (*including the Process Appendices)* and Licensee Specific Appendices

4. Provide an objective view of Licensees performance against targets … it should be easily interrogated to aid in the investigation and verification of them.

5. While the RTM should be an Excel based model, it need not necessarily be a single workbook. To fully meet the requirements it may be necessary to split into multiple workbooks or to produce several versions of the same workbook populated with different data.

The Risk Model implementing the methodology described earlier and the Risk Trading Model are not separate but the same entity. Consequently requirement 3 is immediately achieved, how the remaining four will be is discussed next.

IMPLEMENTATION

Demonstrates the benefit of any trade-off between incremental cost of doing or failing to do work and incremental movements in risk.

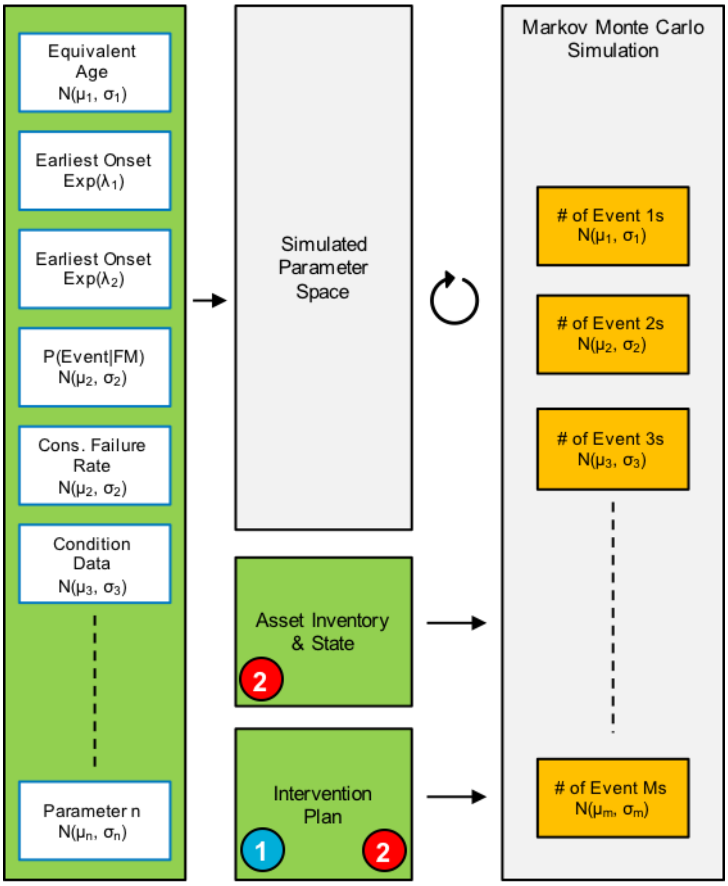
1 Alternative Replacement plans can be uploaded to the model which generate different monetised risk profiles. The model will contain the cost of planned interventions allowing the incremental benefit of alternative plans to be calculated.

Demonstrating why and how investments are prioritised providing specific detail related to Licensees assets, past and future interventions, and work programmes

2 Investments can be prioritised by uploading alternative plans and comparing the NPV of the net risk reduction. The effect of past interventions and asset inventories can be evaluated by using historic asset inventories or with alternative initial asset states.

Provide an objective view of Licensees performance against targets … it should be easily interrogated to aid in the investigation and verification of them.

For a reference configuration of the model it is possible assess how a NGET has performed against risk reduction and investment targets. Finally it will also be possible to compare changes in outputs caused by changing the reference model as future data is introduced.



While the RTM should be an Excel based model, it need not necessarily be a single workbook. To fully meet the requirements it may be necessary to split into multiple workbooks or to produce several versions of the same workbook populated with different data.

Is it not possible to provide the Risk Trading Model as an Excel based model. Outputs from the model will be exported to Excel, enabling comparison and evaluation of different scenarios outside of the model with a consistent format to SPT/SHE-T.