Process Appendix – SHE Transmission plc and SP Transmission

CONTENTS

1. INTRODUCTION

This document provides supplemental information on how SP Transmission and SHE Transmission plc implement the methodology laid out within the Common Methodology (hereinafter referred to as "the Methodology").

SHE Transmission and SP Transmission's Implementation of the Methodology (hereinafter referred to as "the Implementation") is aligned with the requirements set out in *BS EN 60812: Analysis techniques for system reliability – Procedure for failure mode and effects analysis*. This will be demonstrated in detail in Section 2.

The remainder of this document will provide further details on the Implementation. For ease of navigation, it follows as far as possible the same layout as Sections 1 and 2 of the Methodology. Where a part of these sections is not referred to below, it is to be assumed that there is no deviation from, or further information to be added to, the Methodology.

2. ALIGNMENT WITH BS EN 60812

This Section provides the background on how the probability of failure of assets will be determined by this Implementation. Ofgem have requested that probability of failure (PoF) is determined from first principles using Failure Mode Effect Analysis (FMEA).

This Implementation is aligned with the requirements set out in BS EN 60812: Analysis techniques for system reliability – Procedure for failure mode and effects analysis (hereinafter referred to as "BS EN 60812"). Correspondingly, this Section describes how the process used follows the steps needed to perform FMEA as presented in BS EN 60812.

The steps needed to perform FMEA are illustrated in Figure 2.1

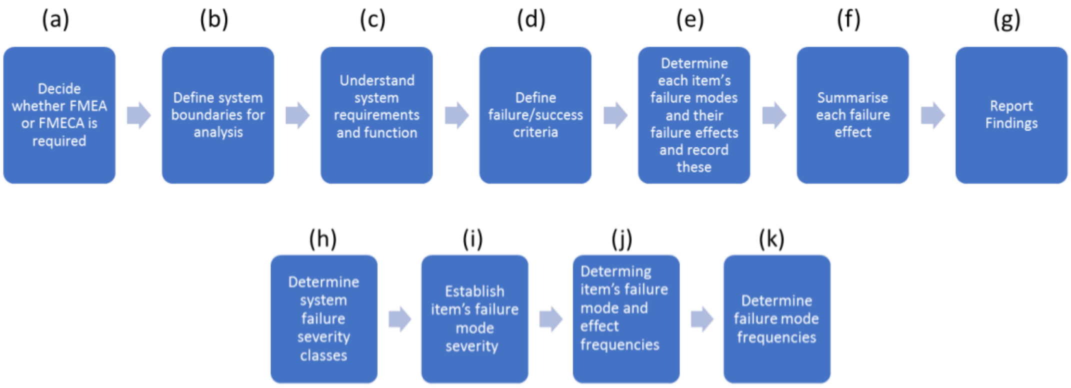

Figure 2.1 - Steps needed to perform FMEA and determine Probability of Failure

BS EN 60812 states that FMEA is preferably applied during the design stage as a means of cost effectively removing or mitigating against potential failure modes for new assets. However, electrical transmission assets are of a mature design and have a proven reliability history. Recognising this, the Implementation has been specifically selected to reflect that it is used to derive the probability of failure curve for mature assets with significant operating history.

As shown in, Figure 2.1 the first step is to determine whether FMEA or FMECA is required. Ofgem require that monetised asset risk is determined; therefore, the Implementation includes the determination of the consequences of failure and asset criticality, i.e. FMECA is required. However, the Criticality determination is explained in detail in the Methodology and, as such, this document presents only those steps directly linked to determining the probability of failure, i.e. steps (b) to (k).

2.1. APPLICATION OF FMEA TO DERIVE PROBABILITY OF FAILURE

BS EN 60812 states that "*The FMEA effort applied to the complex products might be very extensive*". One of the key objectives in determining the approach to implementing the methodology was to ensure that Ofgem's requirement for a common approach to reporting Network Output Measures is achieved in an economically efficient manner.

BS EN 60812 also states that the program plan describing the FMEA analysis "should contain the following points:

- *Clear definition of the specific purposes of the analysis and the expected results;*

- *The scope of the present analysis in terms of how the FMEA should focus on certain design elements. The scope should reflect the design maturity, elements of the design that may be considered to be a risk because they perform a critical function or because of the immaturity of the technology used; and*
- *Participation of design experts in the analysis.*

The approach to the implementation of FMEA has been adopted to ensure that the purpose of the analysis and the scope is directly aligned to meeting the requirements of the common methodology whilst representing optimum economic efficiency. This implementation of FMEA utilises the existing knowledge, experience and historical data relating to the key condition related failure causes for the assets over their lifetime. It takes account of relevant inspection and test protocols to detect these key failure causes. Workshops have been held with transmission engineers to supplement this information in order to identify any additional failure causes, operational stresses and inspection and test protocols that may be relevant for transmission assets.

The scope of the implementation is limited to the following lead assets, as identified in Section 1 of the Methodology:

1. Circuit breakers
2. Transformers
3. Reactors
4. Underground cables
5. Overhead lines
    a. Conductors
    b. Fittings
    c. Towers

2.2. STEP (B): DEFINE SYSTEM BOUNDARIES FOR ANALYSIS

BS EN 60812 states that a number of specific items "*need to be included into the information on the system structure*". This includes information on:

- *"different system elements with their characteristics, performances, roles and functions";*
- *"redundancy level and nature of redundancies";*
- *"position and importance of the system within the whole facility";*

This implementation is applied to electrical transmission assets that are of a mature design and have a proven reliability history. As such, the characteristics, performances and functions of the assets are well understood. Similarly, the redundancy level and the position and importance of individual assets within the overall transmission network is recognised and well documented.

BS EN 60812 states "*The system boundary forms the physical and functional interface between the system and its environment, including other systems with which the analysis system interacts. The definition of the system boundary for the analysis should correspond to the boundary as defined for design and maintenance*".

In this implementation, the asset is considered to represent the most economically efficient level for defining the system.

BS EN 60812 states "*It is important to determine the indenture level in the system that will be used for the analysis. For example, the system can be broken down by function or into subsystems, replaceable units or individual components. Ground rules for selecting the system indenture levels for analysis depend on the results desired and the availability of design information. The following guidelines are useful.*

- *The highest level within the system is selected from the design concept and specified output requirements*

- *The lowest level within the system at which the analysis is effective is that level for which information is available to establish a definition and description of functions. The selection of the appropriate system level is influenced by previous experience. Less detailed analysis may be justified for a system based on a mature design, with a good reliability, maintainable and safety record. Conversely, greater details and a correspondingly lower system level are indicated for any newly designed system or a system with unknown reliability history.*
- *The specified or intended maintenance and repair level may be a valuable guide in determining the lower system levels*."

The Implementation is conducted at the asset level, i.e. at the "system level" in FMEA terms. This is considered to be the appropriate level for assets that are of a mature design and have a proven reliability history, as is the case for electricity transmission assets which have good reliability, maintenance and safety records. This also corresponds to conducting analysis at the level at which maintenance and repairs are conducted, i.e. at the "system level".

Full analysis of both failure rates and outcomes at a lower (sub-component) level is not always economically efficient for mature assets. However, it is essential that all potential failures of sub-components are taken into consideration in the analysis. Specifically, the failure causes are considered at the sub-component level, but the failure effects are captured at the system level. This requires careful analysis of the detection methods to ensure nothing is missed. This is discussed further in Section 5.2.

2.3. STEP (C): UNDERSTAND SYSTEM REQUIREMENTS AND FUNCTION

BS EN 60812 states "*The status of the different operating conditions of the system should be specified, as well as the changes in the configuration or position of the system and its components during the different operational phases.*"

Thus, in order to understand the requirements for the system (i.e. the asset), FMEA requires that the status of the different operating conditions of the system be specified, together with any changes in configuration of the position of the system and its components during the different operational phases. This is used to define the requirements for, say, the minimum levels of performance (e.g. in terms of reliability or safety) being achieved.

This Implementation relates to assets that are of a mature design and have a proven reliability history; therefore, the knowledge and understanding of the system requirements are well defined. The system requirements are clearly documented for each asset in the form of its functional specification in terms of voltage withstand, current carrying capacity, number of operations, environmental operating conditions, etc.

BS EN 60812 states "*The environmental conditions of the system should be specified, including ambient conditions and those created by other systems in the vicinity*."

The environmental conditions of the assets are well known and understood, specifically the physical location and the situation for each asset (i.e. whether it is indoors or outdoors). Information is also collected on the environmental conditions. This information is used, alongside other criteria, to determine the rate of degradation of assets over time and to derive asset health. See Section 2.10 for further information.

2.4. STEP (D): DEFINE FAILURE / SUCCESS CRITERIA

The analysis is concerned with the "failure" of physical assets. Transmission assets are designed and operated with the aim of avoiding failures which result in supply loss and are therefore typically replaced before such failures occur. Such decisions are made by considering the ability of the asset to perform its design function adequately. These types of failure criteria can be broadly defined as "the failure of the asset to perform its designated function". This definition is consistent with the definition of "Functional Failure" which is used in

Reliability Centred Maintenance[1] which states that "A Functional Failure is defined as the inability of any asset to fulfil a function to a standard of performance which is acceptable to the user".

More specifically, electrical assets are required to fulfil a number of functions in the form of electrical, mechanical, operational, safety and environmental capability. This definition leads to the following set of failure criteria for all asset categories:

	Failure criteria
Electrical	The asset fails to perform its designated electrical function (e.g. voltage withstand, current carrying capacity)
Mechanical	The asset fails to perform its designated mechanical function (e.g. suspension of a conductor)
Operational	The asset fails to perform its designated operational function (e.g. responding to trip commands or tap-change instructions)
Safety	The asset fails to perform its designated safety function (e.g. shutters, interlocks, earthing)
Environmental	The asset fails to perform its designated environmental function (e.g. preventing release of gas or oil)

Table 2.1 - Failure Criteria

Each of these failures will manifest itself in many different ways and at different times. The following section analyses the specific failure modes of each asset category to ensure that all potential failures have been considered and that adequate detection methods exits to enable these failures to be identified.

2.5. STEP (E): DETERMINE EACH ITEM'S FAILURE MODES AND THEIR FAILURE EFFECTS

BS EN 60812 provides some general failure modes as shown in Table 2.2, to be considered when determining the failure modes and their failure effects.

	Failure Mode
1	Failure during operation
2	Failure to operate at a prescribed time
3	Failure to cease operation at a prescribed time
4	Premature operation

Table 2.2 - General Failure Modes (from BS EN 60812)

BS EN 60812 states "*Virtually every type of failure mode can be classified into one or more of these categories. However, these general failure modes categories are too broad in scope for definitive analysis; consequently, the list needs to be expanded to make the categories more specific.*

It is important that evaluation of all items within the system boundaries at the lowest level commensurately with the objectives of the analysis is undertaken to identify all potential failure modes. Investigation to determine possible failure causes and also failure effects on subsystem and system function can then be undertaken.

"To assist this function typical failure mode data can be sought from the following areas:

a *for new items, reference can be made to other items with similar function and structure and to the results of tests performed on them under appropriate stress levels;*

[1] Reliability Centred Maintenance, John Mowbray, 1997 – see page 47

- *b* *for new items, the design intent and detailed functional analysis yields the potential failure modes and their causes. This method is preferred to the one in a), because the stresses and the operation itself might be different from the similar items. An example of this situation may be the use of a signal processor different than the one used in the similar design;*
- *c* *for items in use, in-service records and failure data may be consulted;*
- *d* *potential failure modes can be deduced from functional and physical parameters typical of the operation of the item."*

BS EN 60812 also states that "*Failure causes may be determined from analysis of field failures* ". As this Implementation is applied to mature assets that have been in operation over many years, service records and failure data have been used to identify the failure modes. Specifically, the National Equipment Defect Reporting Scheme (NEDeRS®) has been used to identify failure causes. NEDeRS® combines experience of users regarding defects occurring on electrical equipment and associated components and enables appropriate action to be taken. The defects reported include those discovered during inspection after delivery, in commissioning, in operation and during maintenance.

The process used to apply NEDeRS® information to deriving the failure modes and their failure effects is illustrated in Figure 2.2 .

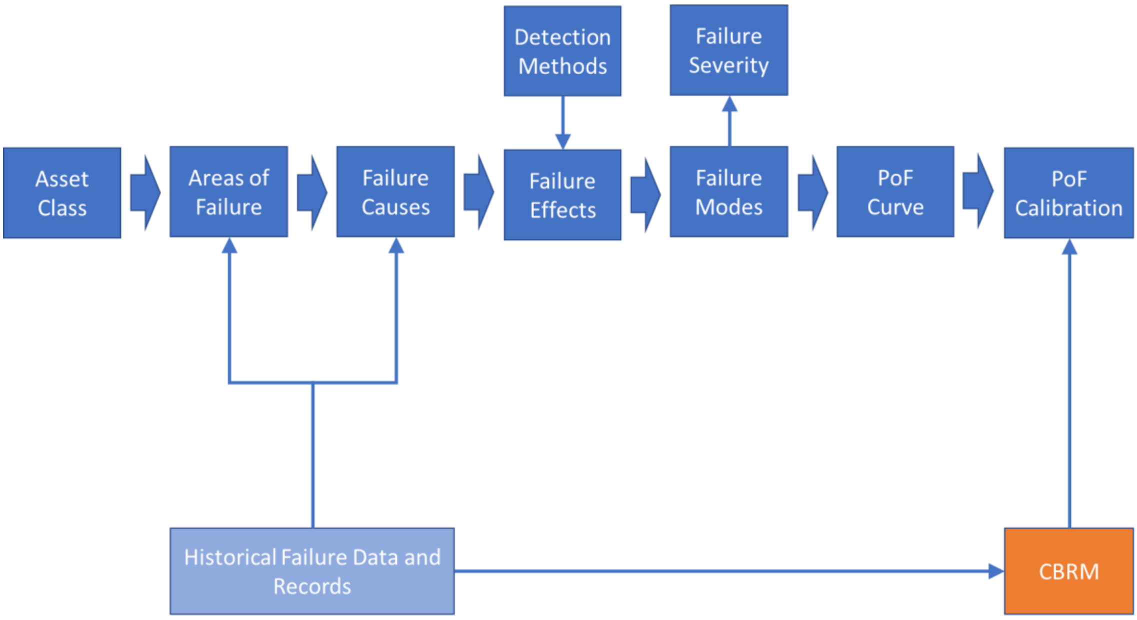

Figure 2.2 - Process used to identify PoF curve using historical data

The types of defects recorded within NEDeRS® fall into one or more of the following categories:

- Dangerous Incident Notice (DIN): the standard form of notification of an incident which resulted or could have resulted in a fatality or serious injury;
- Suspension of Operating Practice (SOP): a notification of a suspension or change in some operational practice or procedure
- National Equipment Defect Report (NEDeR): a defect or operational problem related to an item of plant that is not considered to meet the criteria of a DIN; and
- Defect: a deficiency that is not sufficiently severe to warrant a DIN, SOP or NEDeR, but which is worthy of recording;

Table 2.3 provides an extract showing selected failure areas (i.e. failure item or sub-component at which failures are recorded), as reported in NEDERs®, by asset class. This information is shown in its entirety in Appendix A of this Document.

Failure Area	Asset Class						
	Circuit Breakers	Trans-formers	Reactors	Cables	OHL: Conductors	OHL: Fittings	OHL: Towers
Actuator	✓						
Arc Contact Assembly	✓						
Auxiliary Wiring	✓	✓	✓				
Blast Tube	✓						
Breather		✓	✓				
Busbar Chamber	✓						
Busbar/ Bandjoint	✓						
Bushing	✓	✓	✓				
Cable				✓			
Cable Box	✓	✓	✓	✓			
Cable Termination	✓	✓	✓	✓	✓		
..	..	..	..	..	..	..	..
Isolating contact / Auxiliary contact	✓						
Joggle Chamber	✓						
Key Interlock	✓						
LV Chamber		✓					
Main Tank/Chamber		✓	✓				
Mechanism/ Mechanical	✓	✓	✓		✓	✓	✓
..	..	..	..	..	..	..	..
Pipework		✓	✓				
Porcelain		✓	✓			✓	
..	..	..	..	..	..	..	..
Spouts/ Shutters	✓						
Stress Cone	✓	✓	✓	✓			
Tapchanger Tank		✓	✓				
..	..	..	..	..	..	..	..
Vacuum Interrupter	✓						
Voltage Transformer	✓	✓	✓				

Table 2.3 - Failure Items by Asset Class

NEDeRS® contains a total of 40 potential failure causes. Table 2.3 demonstrates the complex relationship that exists between failure cause and failure area (i.e. sub-component), i.e. each failure cause can potentially affect a large number of sub-components. This is presented in the form of a matrix showing the linkage between failure cause and sub-component for a sample data sub-set in Table 2.4. This information is shown in its entirety in Appendix A of this Document.

Failure Cause	Failure Area										
	Actuator	Arc contact assembly	Auxiliary Wiring	Blast Tube	Breather	Busbar Chamber	Cable Termination	Joggle Chamber	Key Interlock	Mechanism/Mechanical	Power Supply Mode
Accidental contact	✓					✓			✓	✓	
Auxiliary - short circuit			✓						✓	✓	✓
Connector failure	✓		✓			✓	✓	✓	✓	✓	✓
Contacts not made properly	✓	✓	✓	✓			✓		✓	✓	✓
Contamination of internal parts	✓	✓		✓		✓	✓	✓	✓	✓	
Electronic hardware failure/malfunction	✓		✓						✓	✓	✓
Environment	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Faulty design	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Faulty installation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Faulty manufacture	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Ferro resonance		✓		✓		✓	✓	✓			
Interlock	✓	✓	✓	✓					✓	✓	
Lightning	✓	✓		✓	✓	✓	✓	✓			✓
Loss of Vacuum		✓		✓							
Lubrication of components	✓	✓		✓					✓	✓	
Mechanical	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Oil Contamination		✓		✓		✓	✓			✓	
Overload		✓		✓		✓	✓	✓			✓
Oxidation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Partial discharge activity						✓	✓	✓			
Water/Moisture Ingress	✓		✓		✓	✓	✓	✓	✓	✓	✓
Wind/gale					✓						
Accidental contact	✓					✓			✓	✓	

Table 2.4 - Failure Causes by Failure Area

BS EN 60812 states that "*A failure effect is the consequence of a failure mode in terms of the operation, function or status of a system*."

There are a number of potential reasons for an asset to fail; these failures are referred to as functional failures and relate to the inability of the asset to adequately perform its intended function. Hence, functional failures are not solely limited to failure events that result in an interruption to supply.

Any failure has the potential to affect the ability of assets to function as required. Table 2.5 summarises the primary functions of lead assets.

Asset Class	Operation, Function, Status	Failure Criteria
Circuit Breakers	Insulate Conduct Interrupt	Electrical, Operational, Safety, Environmental
Transformers	Insulate Conduct Transform	Electrical, Operational, Safety, Environmental
Reactors	Insulate Conduct Provide reactance	Electrical, Operational, Safety, Environmental
Underground Cables	Insulate Conduct	Electrical, Safety, Environmental
Overhead Lines (Conductors)	Conduct Mechanical Support	Electrical, Mechanical
Overhead Lines (Fittings)	Insulate Mechanical Support	Electrical, Mechanical
Overhead Lines (Towers)	Mechanical Support	Mechanical, Safety

Table 2.5 - Operation, Function and Status of Lead Assets

BS EN 60812 states that "*the way in which the failure is detected and the means by which the user or maintainer is made aware of the failure*" should be determined.

There is a number of different detection methods employed to detect failures of transmission network assets (i.e. when the asset fails to perform its required function). These detection methods can be classified as follows:

- System protection
- On-line monitoring
- Supervisory system
- Maintenance
- Measurement
- Visual inspection

There is a direct linkage between the detection method and the failure effect. Any failure resulting in the activation of system protection leads to the isolation of the asset from the remainder of the network and, in some circumstances, could lead to a loss of supply. The nature of some failures detected by routine maintenance or visual inspection, however, means the asset can remain in service until such a time that the repair is carried out.

The linkage between the detection method and the failure effect is highlighted in Table 2.6. These effects take into consideration the failure compensating provisions that are in place to prevent or reduce the effect of the failure mode, as within BS EN 60812.

Failure Effect Category	Detection Method					
	System Protection	On-Line Monitoring	Supervisory System	Maintenance	Measurement	Visual Inspection
No unplanned outage, no planned outage required. No damage caused to the system.				✓	✓	✓
No unplanned outage, planned outage required. No damage caused to the system.		✓	✓	✓	✓	✓
Unplanned outage. Any damage to the system is limited, and repairs can be undertaken within a few days.	✓					
Unplanned outage, requires extensive repair, which typically takes one to two weeks.	✓					
Unplanned outage, catastrophic damage has occurred. Repair / replacement takes an extensive period of time (several weeks or months)	✓					

Table 2.6 - Detection Methods

In this context, the term 'outage' refers to the asset being 'taken out of service'. This could be as a result of the activation of system protection (i.e. an unplanned outage), or the isolation of the asset while repairs are undertaken (i.e. a planned outage).

The use of these categories to define the failure effects ensures alignment with the way that failures have been recorded. The categories also used to define the failure modes, see Section 2.6. This has the advantage of enabling the probability of failure curve for each of these failure modes to be calibrated against historical fault records.

2.6. STEP (F): SUMMARISE EACH FAILURE EFFECT

The failure effects are summarised in Table 2.7

Circuit Breakers	
1	A failure that does not cause an unplanned outage. Repairs can be undertaken without taking the asset out of service.
2	The circuit breaker fails to operate when called to do so, resulting in a larger unplanned outage than would be expected. Investigation and repairs may be required before the device can be returned to service.
3	A failure that causes an unplanned outage which can be repaired. The duration of the repair exceeds 24 hours but is less than 10 days.
4	A failure that causes an unplanned outage and extensive damage. Where repairs are possible the duration of any works will exceed 10 days, or the failure will result in the retirement of the failed asset and require the installation of a new replacement asset.
Transformers	
1	A failure that does not cause an unplanned outage. Repairs can be undertaken without taking the asset out of service.
2	A failure that does not cause an unplanned outage, but requires a planned outage for repairs to be undertaken. The duration of the repair is three days or less.
3	A failure that causes an unplanned outage which can be repaired. However, the duration of the repair exceeds three days but is less than 10 days.
4	A failure that causes an unplanned outage which causes extensive damage. Where repairs are possible, the duration exceeds 10 days. Alternatively, the failure requires the installation of a new asset.
Reactors	
1	A failure that causes an unplanned outage which can be repaired and returned to service within three days.
2	A failure that causes an unplanned outage which can be repaired. However, the duration of the repair exceeds three days but is less than 10 days.
3	Major: A failure that causes an unplanned outage which causes extensive damage. Where repairs are possible, the duration exceeds 10 days. Alternatively, the failure requires the installation of a new asset.
Underground cables	
1	A failure that does not cause an unplanned outage. The repair can be conducted in a planned manner, using a planned outage.
2	A failure causing an unplanned outage.
Overhead lines – conductors	
1	A failure that requires a repair; however does not either cause or require an outage.
2	A failure that does not cause an unplanned outage, but requires a planned outage for repairs to be undertaken.
3	A failure that causes an unplanned outage, but can be repaired within a week.
4	A failure that causes an unplanned outage and repair takes more than a week or the asset needs to be replaced.
Overhead lines - fittings	
1	Failure does not cause an outage and repair can be undertaken without an outage
2	Failure does not cause an unplanned outage, but requires a planned outage for repair.
3	Failure causes an unplanned outage.
Overhead lines - towers	
1	Failure does not cause an outage and repair can be undertaken without an outage
2	Failure does not cause an unplanned outage, but requires a planned outage for repair.
3	Failure causes an unplanned outage.

Table 2.7 - Failure Effects

2.7. STEP (H): DETERMINE SYSTEM FAILURE SEVERITY CLASSES

BS EN 60812 states that "*Severity is an assessment of the significance of the failure mode's effect on item operation*."

The Standard also provides some general guidance on severity classification via the examples listed in Table 2.8

Severity Classification	Consequences
Catastrophic	A failure mode which could potentially result in the failure of the system's primary functions and therefore cause serious damage to the system and its environment and/or personal injury
Critical	A failure mode which could potentially result in the failure of the system's primary functions and therefore cause serious damage to the system and its environment, but which does not constitute a serious threat to life or injury.
Marginal	A failure mode, which could potentially degrade system performance function(s) without appreciable damage to system or threat to life or injury.
Insignificant	A failure mode, which could potentially degrade system performance function(s) but will cause no damage to the system and does not constitute a threat to life.

Table 2.8 - BS EN 60812 Illustrative Example of Severity Classification

2.8. STEP (I): ESTABLISH ITEM'S FAILURE MODE SEVERITY

The failure effects as listed in Section 2.6 can be mapped directly onto these failure severity classifications, as shown below. The failure severity of the failure modes considered in this implementation is shown in Table 2.9.

	Failure Mode		Failure Severity
Circuit Breakers	1	A failure that can be repaired, does not cause or require a planned outage	Defect
	2	A circuit breaker fails to operate when called to do so, resulting in a larger unplanned outage than would be expected. Investigation and repairs may be required before the device can be returned to service.	Minor
	3	A failure that causes an unplanned outage which can be repaired the duration of the repair exceeds 24 hours but is less than 10 days.	Significant
	4	A failure that causes an unplanned outage and extensive damage. Where repairs are possible the duration of any works will exceed 10 days, or the failure will result in the retirement of the failed asset and require the installation of a new replacement asset.	Major
Transformers	1	A failure that causes an unplanned outage which can be repaired and returned to service within three days.	Minor
	2	A failure that causes an unplanned outage which can be repaired. However, the duration of the repair exceeds three days but is less than 10 days.	Significant
	3	Major: A failure that causes an unplanned outage which causes extensive damage. Where repairs are possible, the duration exceeds 10 days. Alternatively, the failure requires the installation of a new asset.	Major
Reactors	1	A failure that causes an unplanned outage which can be repaired and returned to service within three days.	Minor
	2	A failure that causes an unplanned outage which can be repaired. However, the duration of the repair exceeds three days but is less than 10 days.	Significant
	3	A failure that causes an unplanned outage which causes extensive damage. Where repairs are possible, the duration exceeds 10 days. Alternatively, the failure requires the installation of a new asset.	Major
Cables	1	A failure that does not cause an unplanned outage. The repair can be conducted in a planned manner, using a planned outage.	Minor
	2	A failure causing an unplanned outage.	Major
Overhead lines – conductors	1	A failure that requires a repair however does not either cause or require an outage.	Defect
	2	A failure that does not cause an unplanned outage, but requires a planned outage for repairs to be undertaken.	Minor
	3	A failure that causes an unplanned outage, but can be repaired within a week.	Significant
	4	A failure that causes an unplanned outage and repair takes more than a week, or the asset needs to be replaced.	Major
Overhead lines - fittings	1	Failure does not cause an outage and repair can be undertaken without an outage	Minor
	2	Failure does not cause an unplanned outage, but requires a planned outage for repair.	Significant
	3	Failure causes an unplanned outage.	Major
Overhead lines - towers	1	Failure does not cause an outage and repair can be undertaken without an outage	Minor
	2	Failure does not cause an unplanned outage, but requires a planned outage for repair.	Significant
	3	Failure causes an unplanned outage.	Major

Table 2.9 - Failure Mode Severity

2.9. STEP (J): DETERMINE ITEM'S FAILURE MODE AND EFFECT FREQUENCIES

The following approach has been adopted in order to determine the failure mode effect frequency;

- Determine the general form or shape of the failure effect frequency distribution curve;
- Express the failure effect frequency mathematically so that values can be derived for individual assets. This has been achieved via the following two stages:
  - Express the shape of the curve using a mathematical expression
  - Determine the absolute values of the failure effect frequency and ultimately the failure mode frequencies. This is described in Section 0.

In order to determine the general form of the failure effect frequency curve, the failure causes have been sub-divided into the following categories

- Failures that are linked to degradation and asset deterioration, i.e. time based failures
- Failures not linked to degradation and deterioration, i.e. which are not related to time. These can be further sub-divided as follows:
  - Those related to 'internal' issues associated with the asset itself, such as those linked to manufacturer/model issues, design, installation, maintenance and obsolescence.
  - Those related to 'external' issues such as lightning or other weather related events.

An example of this mapping is provided in Table 2.10. This information is shown in its entirety in Appendix A of this Document.

Fault Cause	Failure categorisation		
	Time Based	Non-Time Based	
	(Condition)	(Internal)	(External)
Accidental contact			✓
Connector failure	✓		
Faulty design		✓	
Mechanical	✓		
Oil contamination	✓		
Oxidation	✓		
Wind/gale			✓

Table 2.10 - Failure Categorisation by Cause

General reliability theory[2] suggests that there are six failure patterns that occur in practice, as summarised in Table 2.11.

Practical experience suggests that:

- Non-time based failures (by definition) are random failures, and occur at a consistent level over the life of the asset.
- Time-based failures follow the 'wear out' pattern, i.e. the probability of failure increases over time.

Combining these two elements together, as illustrated in Figure 2.3 therefore provides an estimate of the form of the failure effects frequency curve. This indicates that there is an initial phase where the rate of failure is at a constant low level, with failures then increasing as the asset reaches the end of its life. Analysis shows that all the identified fault causes lead to one or more of the specified failure categories.

[2] Reliability Centred Maintenance, John Mowbray, 1997

This does not preclude that a sub-set of the population may exhibit infant mortality or initial break-in patterns of failure in addition to the 'wear out' curve. However, the curve shown in Figure 2.3 is considered to best describe the failure effects frequency curve of an asset population as a whole.

No.	Failure Pattern	Description
1	Bathtub	A high probability of failure when the equipment is new, followed by a low level of random failures, and followed by a sharp increase in failures at the end of its life.
2	Wear out	A low level of random failures, followed by a sharp increase in failures at the end of its life.
3	Fatigue	A gradually increasing level of failures over the course of the equipment's life.
4	Initial break-in period	A very low level of failure followed by a sharp rise to a constant level
5	Random	A consistent level of random failures over the life of the equipment with no pronounced increases or decreased related to the life of the equipment.
6	Infant mortality	A high initial failure rate followed by a random level of failures

Table 2.11 - Six Patterns of Failure

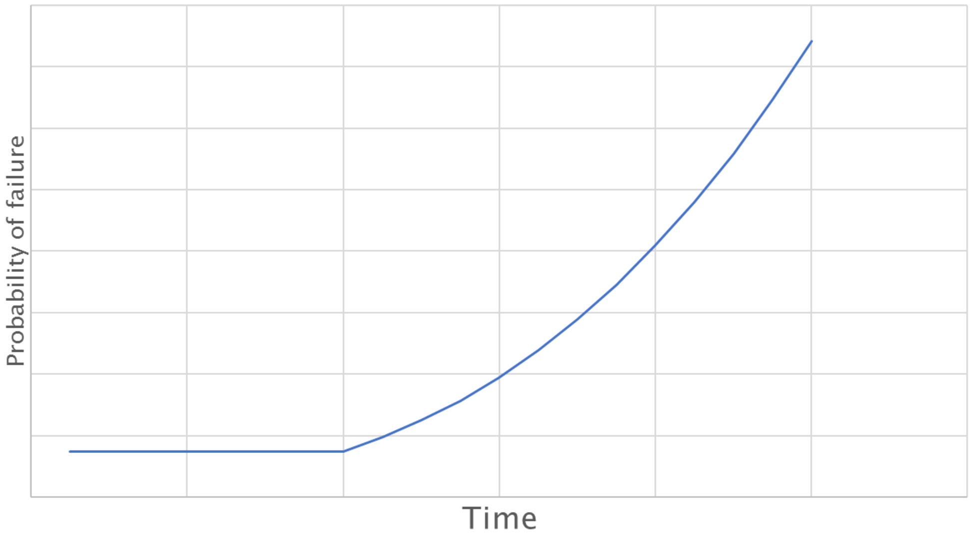

Figure 2.3 - Form of the Probability of Failure Curve

This Implementation links probability of failure to asset condition. This approach is a key step in the process as it enables the probability of failure curve to be calibrated against historical failure records and takes account of operating experience and knowledge. More information on the mathematical expression of the Probability of Failure Curve can be found in Section 5.4.

2.10. STEP (K): DETERMINE FAILURE MODE FREQUENCIES

As described above, the concept of the End of Life Indicator is used to embody all of the factors that may influence each failure mode's probability of failure. The detail of the End of Life Indicator formulation is different for each asset class, reflecting the different information and the different types of degradation processes. There is, however, an underlying structure for all asset groups as outlined below:

For a specific asset, an initial (age related) End of Life Indicator is calculated using knowledge and experience of its performance and expected lifetime, taking account of factors such as original specification, manufacturer, operational experience and operating conditions (duty, proximity to coast, etc.). Further details are given in Section 5.4 and the Company Specific Appendices.

Information that is indicative of condition is used to create additional 'factors' that modify the initial End of Life Indicator. This includes information that cannot be directly related to specific degradation processes, such as factors relating to fault / defect history and reliability issues associated with specific equipment types (e.g. different manufacturers). It also includes information related to specific degradation processes that identify potential end of life conditions (e.g. corrosion), but is not generally considered sufficient to provide a definitive indication of asset condition independently of other information. Whilst this information is not used to provide a specific End of Life Indicator, it can be used to define a minimum value for the asset (see Section 5.4).

Where condition information related to specific degradation process can be used to identify end of life conditions with a high degree of confidence (e.g. dissolved gas analysis of transformer oil provides a definitive indication of the health of the transformer regardless of other information available), this is used to directly derive an End of Life Indicator for the asset. This could include condition information derived from specific tests or very detailed visual condition information obtained from helicopter inspections of overhead lines. Where appropriate, the values derived from such tests can be used in preference to the modified age based End of Life Indicator described above. Further details are found in Section 5.4

In summary, the current End of Life Indicator of an individual asset is determined by comparing the values derived for intermediate End of Life Indicators. This can be represented by the schematic in Figure 2.4

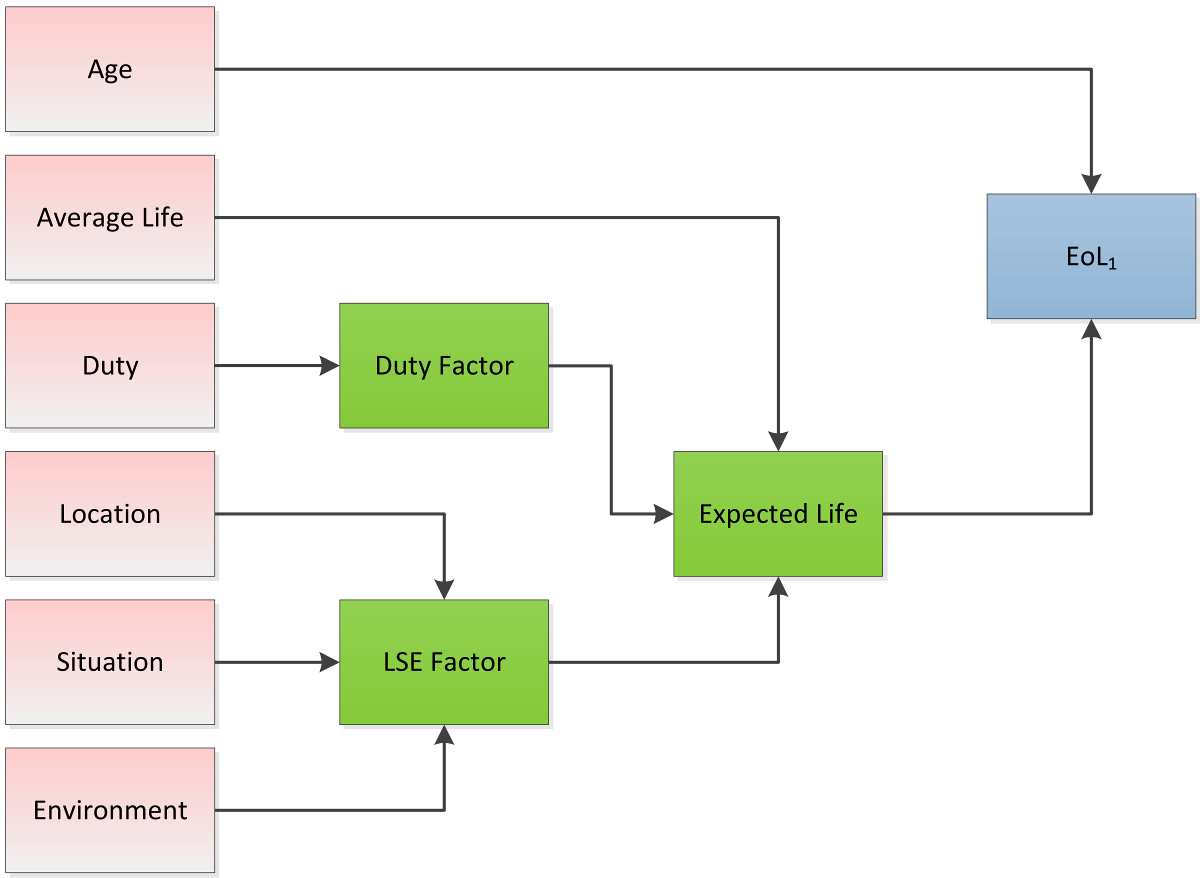

Figure 2.4 - Derivation of Current End of Life Indicator

The derivation of each of the components in Figure 2.4 is described in more detail in Section 6.

3. METHODOLOGY OVERVIEW

3.1. ASSETS

In order to ascertain the overall level of risk, the methodology will calculate Asset Risk for lead assets only, namely:

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

Whilst each TO owns a small <132kV asset base, lead assets are deemed by Ofgem to be those operating at 132kV and above.

3.2. MATERIAL FAILURE MODE

The failure criteria for each asset is a state that prevents the achievement specified requirement and function. By implication, any state that does not prevent or impede the achievement of the specified requirement and function is not regarded as a failure. This Implementation of the Methodology considers only the condition-related failure modes with measurable effects on the specified requirement and function.

The Implementation allows for up to five condition-related failure modes and each failure mode is defined according the severity of the consequences. In order to adequately assess the effect or criticality of each failure mode (in accordance with Section 5.2.9 of EN 60812), these definitions are specific to each asset class and are defined in the relevant section

3.3. PROBABILITY OF DETECTION

The probability of detecting and acting upon the failure mode is already covered in the definition of the failure modes and the use of actual data on the number of failures to calibrate the model (i.e. if a failure mode if usually detected early then this will reflected in the fact that more of the failures will be in the category addressed by planned outages.

3.4. PROBABILITY OF CONSEQUENCE

As stated in the common methodology, this function is used when a failure mode is mapped to multiple effects. However, as this deployment of the methodology considers only the condition-related failure modes with measurable effects on the specified requirement and function, there is a one-to-one mapping from failure mode to effect and, therefore, this is not required.

4. TREATMENT OF UNCERTAINTY

The modelling of asset degradation and failure involves a degree of uncertainty. This is especially the case with transmission assets, which are inherently very reliable and do not always produce clear indicators of degradation or incipient failure. It is therefore essential that any methodology is fully tested and any source of uncertainty fully documented.

The degradation models described in this Implementation contain a number of non-linear elements (in the form of caps, collars or discontinuous functions). Therefore, the actual level of uncertainty in the results will depend to some degree on the input data; for some results, the output will be highly certain and for others (especially at the extremes of the model boundaries), the output will be less certain.

To enable uncertainty to be determined, the following principles must be adopted regarding input data:

- All input data and calibration data will be referenced to its source, wherever possible.
- Where input data or calibration data is estimated (rather than sourced directly) the process by which the estimate was reached will be documented.
- The uncertainty or confidence level should be stated for each input parameter.

Provided the above records are kept, it will then be possible to carry out the sensitivity testing and assessment of uncertainty described in the Methodology.

5. FMEA

As stated within BS 60812, "*The lowest level within the system at which the analysis is effective is that level for which information is available… Less detailed analysis may be justified for a system based on a mature design, with a good reliability, maintainability and safety record*". This deployment of FMEA is a flexible and practical implementation of theory which has been shown to align with BS 60812.

It is not a top down approach, but a system level approach (e.g., transformer) rather than a sub-component level approach (e.g., tapchanger selector). The advantage of this approach is that the same failure mode effects are still considered without the level of uncertainty required for sub-component level analysis.

This system level approach looks at failure modes and their effects, whilst the subcomponent level approach looks at the causes of these failure modes. This subcomponent level approach necessitates a degree of assumption as it requires the operator to define the most likely failure modes (and effects) for each failure cause.

5.1. UNDERSTANDING FAILURE CAUSE TYPES ON TO ASSETS

BS 60812 states:

"*The identification and description of failure causes is not always necessary for all failure modes identified in the analysis. Identification and description of failure causes, as well as suggestions for their mitigation should be done on the basis of the failure effects and their severity. The more severe the effects of failure modes, the more accurately failure causes should be identified and described. Otherwise, the analyst may dedicate unnecessary effort on the identification of failure causes of such failure modes that have no or a very minor effect on system functionality*."

In line with the Standard and as discussed in Section 2.2, this Implementation does not require the documentation of all failure causes for each failure mode. As electrical assets are based on mature designs with many years of experience of the assets in service, the failure causes are well researched and understood, with many years worth of publications, failure investigations and in-service experience of most designs. As such, mitigations for these failure causes are also relatively mature and have resulted in proven design changes, or the ability to detect these failure causes before they lead to catastrophic failure of the asset. This methodology takes this ability to detect the failure causes into consideration when defining the data used to calculate the probability of failure. By providing a flexible framework for the probability of failure calculation, the methodology can take account of any variation in failure causes and detection methods between different asset designs.

Although the potential failure causes could be identified and documented for every failure mode for every asset type, this is considered to be unnecessary effort for a mature and well understood asset base. In addition, a significant number of the failure causes will be exhibited in the same way and have the same severity of their effect e.g. a gassing transformer may be caused by a high resistance connection, movement of the winding, failure of the insulation etc., but all have the potential to result the same failure effect e.g. a Buchholz trip which requires further investigation. Only after investigation will the actual cause of the failure be evident, so the use of field data to define the failure rates for the each of the failure effects and related failure modes is considered to give a more reliable output, as stated in BS 60812:

"*Failure causes may be determined from analysis of field failures or failures in test units. When the design is new and without precedent, failure causes may be established by eliciting the opinion of experts*."

5.2. FAILURE MODES

As discussed in Section 0, this Implementation includes the ability to model several failure modes. The failure modes are grouped in the same way as the common methodology, with the failure modes may be defined as:

- Defect: A failure that can be repaired with a planned outage and returned to service within 24 hours.
- Minor failure: A failure that causes an unplanned outage which can be repaired and returned to service within 24 hours.
- Significant failure: A failure that causes an unplanned outage which can be repaired; the duration of the repair exceeds 24 hours but is less than 10 days.
- Major failure: A failure that causes an unplanned outage which causes extensive damage. Where repairs are possible, the duration exceeds 10 days. Alternatively, the failure requires the installation of a new asset.

The failure modes will also be inherently considered at the level below these groupings so that consideration of the severity (consequence) of failure, and failure rates can be aligned to actual failure data. Examples for a transformer are shown below:

Defect	e.g. External damage to transformer
Minor Failure	e.g. Buchholz trip – no evident fault
Significant Failure	e.g. Bushing or tapchanger failure requiring replacement of component
Major Failure	e.g. Winding failure requiring replacement of asset

The failure modes considered in this methodology, along with their effects and failure rates, are designed to be completely flexible so that they can be aligned with the actual failure modes experienced for an asset group and aligned with actual failure data. For example, failure modes used in transmission may be calibrated differently to those used for distribution assets in cases where inherently different management strategies are applied.

5.3. DETECTING FAILURE MODES

The standard states that “For each failure mode, the analyst should determine the way in which the failure is detected and the means by which the user or maintainer is made aware of the failure.”

As the failure modes are defined at system level in this Implementation and directly linked to the failure effects, the some of the failure modes will be detected if an outage occurs, others will be detected during inspection, maintenance or testing of the asset, and these detection methods will generally be aligned with the data included in determination of the asset condition. As such the End of Life and Probability of Failure can be directly linked through the inclusion of the appropriate measurement data.

5.3.1. CONSEQUENCE OF FAILURE MODES

As stated above, only the failure modes with measurable effects on the specified requirement and function are considered. The failure modes are summarised according to the severity of the failure effect.

The failure severity classifications used in the Implementation are shown in Table 5.1

Severity Classification	Consequences
Defect	A failure that causes no damage to the system or the environment. The failure does not constitute a threat to life or injury. The asset can remain operational while awaiting repair. The asset does not need to be taken out of service for any repairs which typically can be undertaken as part of routine maintenance activities.
Minor	A failure that results in minimal damage to the system or environment is minimal. The failure does not constitute any appreciable increased threat to life or injury. The repair can typically be undertaken within a short period (within three days), and may require the asset to be taken out of service.
Significant	A failure that results in the asset being taken out of service until the repair can be effected. The damage to the system is minimal. The failure constitutes a modest increased threat to life or injury and of damage to the environment. The asset can usually be repaired, but the repair typically exceeds three days but is less than 10 days.
Major	A failure that results in extensive damage to the system and the environment. There is an appreciable increased threat to life or injury. If the asset can be repaired, the repair takes several weeks or months. In many cases, the asset must be replaced.

Table 5.1 - Severity Classifications

These failures represent the broad classification of failures based on experience and operational knowledge. Applying the process described in Section 2.5 shows that every potential failure area of every asset class results in a detectable fault in at least one of the above severity classifications.

This technique of summarising consequences according to the severity of each failure mode has two advantages:

- Only those failure modes with material effects are included, avoiding any unnecessary analysis of failure modes that do not have material effects, and;
- Direct alignment with the failure severity classification, thereby reducing any uncertainty in the mapping of failure effect to failure severity.

This approach has been found to give accurate, reproducible results using generally available data and as a result has been widely adopted throughout the industry both within Great Britain and overseas. For further information on this approach, see Section 6.2.

5.4. PROBABILITY OF FAILURE P(F)

5.4.1. INITIAL AGEING RATE

The Initial Ageing Rate is needed to determine the rate of change of the EoL Indicator. The standard approach adopted is to estimate the time for the EoL Indicator to move from 0.5 (i.e. a new asset) to 5.5 (the end of an asset's anticipated life and the point at which the probability of failure starts to rise significantly (see Section 2.9 for further details). By definition, the time $(t_2 - t_1)$ in Equation 6 is the Anticipated Life of the asset as defined in Section 5.4.2.

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

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

Equation 1

where:

$\mathrm{EoL}_{\mathrm{MAL}}$ = EoL Indicator of the asset when it reaches its Modified Anticipated Life (set to 5.5)

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

$\mathrm{AAL}_{\mathrm{i}}$ = Anticipated Asset Life, i (as determined using Equation 2)

5.4.2. ANTICIPATED ASSET LIFE

The Anticipated Asset Life is the age of an asset, in years, at which it would be first expected to observe significant deterioration (defined as a EoL of 5.5), taking into consideration location and/or duty in addition to the asset type. It is derived from the Average Life (see Section 5.4.3) of the asset and varies depending on the operating conditions for the asset as follows:

$$\mathrm{AAL_i} = \frac{\mathrm{AAL_{N,i}}}{\mathrm{F_{Duty,i}} \cdot \mathrm{F_{Loc,i}}}$$

Equation 2

where:

$\mathrm{AAL_{N,i}}$ = Average Life of asset i

$\mathrm{F_{Duty,i}}$ = Duty Factor of asset i

$\mathrm{F_{Loc,i}}$ = Location Factor of asset i

5.4.3. AVERAGE LIFE

The Average Life of an asset is the time (in years) in an asset's life when it would be expected to first exhibit significant deterioration based on consideration of the asset type, taking account of factors such as original specification and manufacturer. This corresponds to a EoL Indicator of 5.5.

5.4.4. FACTORS WHICH MAY INFLUENCE PROBABILITY OF FAILURE

5.4.4.1. DIFFERENTIATORS

As discussed in Section 0, there may be factors that change the probability of failure. Within this Implementation, these differentiators are:

- Duty (individually described within each asset section)
- Location, Situation and Environment (LSE)

For each transformer, the LSE factor is calculated from the following variables (Details on the possible values assigned to these variables can be found in the Company Specific Appendices):

- Distance to body of salt water
- Altitude
- Corrosion rating
- Situation
- Environment

F_{LSE} can then be determined by combining the outputs of the three LSE factors.

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

$$L_E = L_A \times (F_{LSE} \times F_{DY})$$

Equation 3

This expected life is then combined with the average life for that asset type to determine EoL_1.

5.4.4.2. MODIFIERS

Modifiers change the rate at which an asset's Probability of Failure increases. Within this Implementation, these modifiers are:

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

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

Visual External Condition Factors

The observed condition of the transformer is evaluated through visual assessment by operational staff. Several components of the transformer are assessed individually and assigned a condition. Condition is assessed on a 1-5 scale (1 = satisfactory, 5 = immediate replacement required). Each component's condition is weighted differently based on the significance of the component. These components are combined to produce an overall scale and a Condition factor is produced.

Defects

The defect module searches the input data defect list to identify any defects associated with each asset. The defects, in the form of stock phrases, automatically populate a defects calibration table against which users assign a defect severity score. Once the calibration table has been set, the defect module calculates a defect score for each asset, and uses this score to determine a defect factor, which can be overridden by a poor defect history exception report. As with the condition factor outlined above, it is possible to set minimum HIs for any identified defects, where this has taken place the model will identify any minimum EoL indices, and set them aside for use later in the process.

Family Reliability

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

Test Results

Where tests have been undertaken, the results (pass, suspect or fail) for each test type are used to derive individual test factors (and if desired minimum EoL indices) and are then combined in order to produce an overall test factor. The overall test factor is included in the formation of modifying factor FV1, while any defined minimum EoL indices are set aside for use later in the process.

Operational Restrictions

When a significant issue is identified regarding a family of transformers, an Operator can issue a NEDeR which notifies all other operators. This is called an Operational Restriction, or OR. Each OR is assigned a severity, which then generates an Operational Restriction factor.

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

5.4.5. MAPPING END OF LIFE MODIFIER TO PROBABILITY OF FAILURE

As discussed in previous Sections, this Implementation uses this asset-specific information; from both intrusive and non-intrusive inspections to derive a series of modifiers and differentiators which are then used to produce an overall End of Life Modifier. From that, the asset's failure mode frequency or Probability of Failure (PoF) is derived (this is described in more detail in the asset-specific sections of this document). The relationship between the condition related probability of failure and time is shown schematically in Figure 2.3.

6. CALCULATING PROBABILITY OF FAILURE

As shown in Figure 2.3, the relationship between the condition related probability of failure and time is not linear. An asset can accommodate significant degradation with very little effect on the risk of failure. Conversely, once the degradation becomes significant or widespread, the risk of failure rapidly increases. The use of a standard relationship between PoF and asset health means that End of Life Indicators for all different types of assets (transformers, cables, switchgear, OHLs) have a consistent meaning. The significance of any individual End of Life Indicator value or the distribution of values for a population can be immediately appreciated. Comparisons between different assets and different asset groups can be made directly.

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

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

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

Mathematical modelling[3] using simulated data indicates that the use of an exponential function provides a predicted failure rate that generally falls in the range of the simulated predictions up to about year 15. After this time, the function starts to give predicted failure rates that are too high. A better approach is considered to be a hybrid form of the cubic function as shown in Equation 4[4]. This allows for the probability of failure to be constant for low value End of Life Indicators (i.e. for assets in good condition) before increasing rapidly as the End of Life Indicator increases (i.e. as the item begins to significantly degrade). The cubic function is considered to model asset behaviour more closely than the exponential.

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

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

and

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

Equation 4

where:

PoF	=	probability of failure
EOL	=	End of Life Indicators
k & c	=	constants

[3] "Applying Markov Decision Processes in Asset Management" (M Black) - PhD Thesis,(2003)
[4] "Comparing probabilistic methods for the asset management of distributed items" (M Black, AT Brint and JR Brailsford) - ASCE J. Infrastructure Systems (2005)

$\mathrm{EoL_{lim}}$ = EoL Indicator limit below which the probability of failure is constant.

The value of c fixes the relative values of the probability of failure for different modifiers (i.e. the slope of the curve) and k determines the absolute value; both constants are calibration values which are set for each asset class and for each failure mode. Further information on determining the values for c and k is found in Sections 6.1 and 6.2 respectively.

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

6.1. DETERMINATION OF C

The value of c is the same for all Asset Categories and has been selected such that the PoF for an asset in the worst condition is ten times higher than the PoF of a new asset.

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

6.2. DETERMINATION OF K

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

The value of k in Equation 5 is derived by consideration of:

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

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

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

Thus, the value of k is calculated as follows:

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

Equation 5

where:

n = the number of assets in asset group I

6.3. CALIBRATION AGAINST VERY LOW OBSERVED FAILURE RATES

The electricity industry recognises that one of the most challenging aspects in modelling the performance of transmission assets is their very high reliability[5]. While there may be numerous records of "defects" or "minor failures", evidence of "major failures" may not exist and the observed failure rate for a particular asset category by particular network operators may tend towards zero. This potentially leads to an inaccurate determination of asset condition risk.

Given this widely-recognised problem (and the resulting lack of data available to each network operator), the IEC White Paper on "Strategic asset management of power networks"[6] recommends that "a standardized set of functions to which to fit historical data could be specified, together with a method for determining which particular function to use for a given data set, considering environment and load conditions. This would dramatically improve the accuracy of service life estimation across businesses and allow benchmarking and comparison of various approaches". This is the approach taken by in this Implementation, but it is of course dependent on the effective exchange of industry-wide data to enable effective calibration and benchmarking.

Fortunately, such exchanges do exist, including industry-wide reliability assessments, such as EPRI's Industry-Wide Substation Equipment Performance and Failure Database[7] or UMS's International Transmission Operations & Maintenance Study[8]. Where failure rates are not supported by direct field evidence, such data should be used as the basis of review and benchmarking wherever possible.

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

6.4. END OF LIFE

End of life (EoL) can be defined as when the condition related probability of failure becomes unacceptable. It may be difficult to define unacceptable PoF, and indeed it may vary from asset to asset. However, as the importance of the asset increases, the limit of acceptable PoF will fall. With the sharply rising EoL / PoF relationship (see Figure 2), it would be expected that EoL will be when the EoL indicator reaches a value somewhere between 6 and 10. Typically, end of life is defined as an EoL indicator of 7 or greater.

The condition of the overall asset population is monitored to ensure that replacement/refurbishment volumes are sufficient to maintain sustainable levels of reliability performance, to manage site operational issues associated with safety risks and to maintain or improve environmental performance. Aspects such as strategic spares holdings and refurbishment capabilities are managed to ensure these sustainable levels of reliability performance are maintained and to maintain or improve safety and environmental performance.

Although transmission assets are often complex, multi-component items of plant, within this Implementation each is considered as an individual self-contained 'system' on a per asset basis.

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

Asset management information is fed into the Implementation in order to produce a EoL indicator for each asset, which is referred to as $EoL_{(Y0)}$. It is from this 'system' EoL indicator a probability of failure, (PoF), is calculated for a number of defined failure modes.

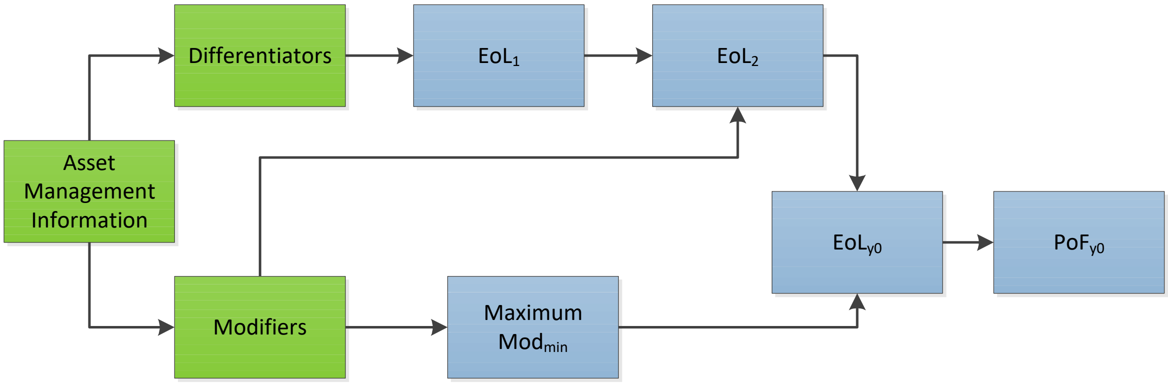

Figure 6.1 - Implementation Overview

6.4.1. DERIVATION OF THE INITIAL EOL INDICATOR, EOL_1.

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

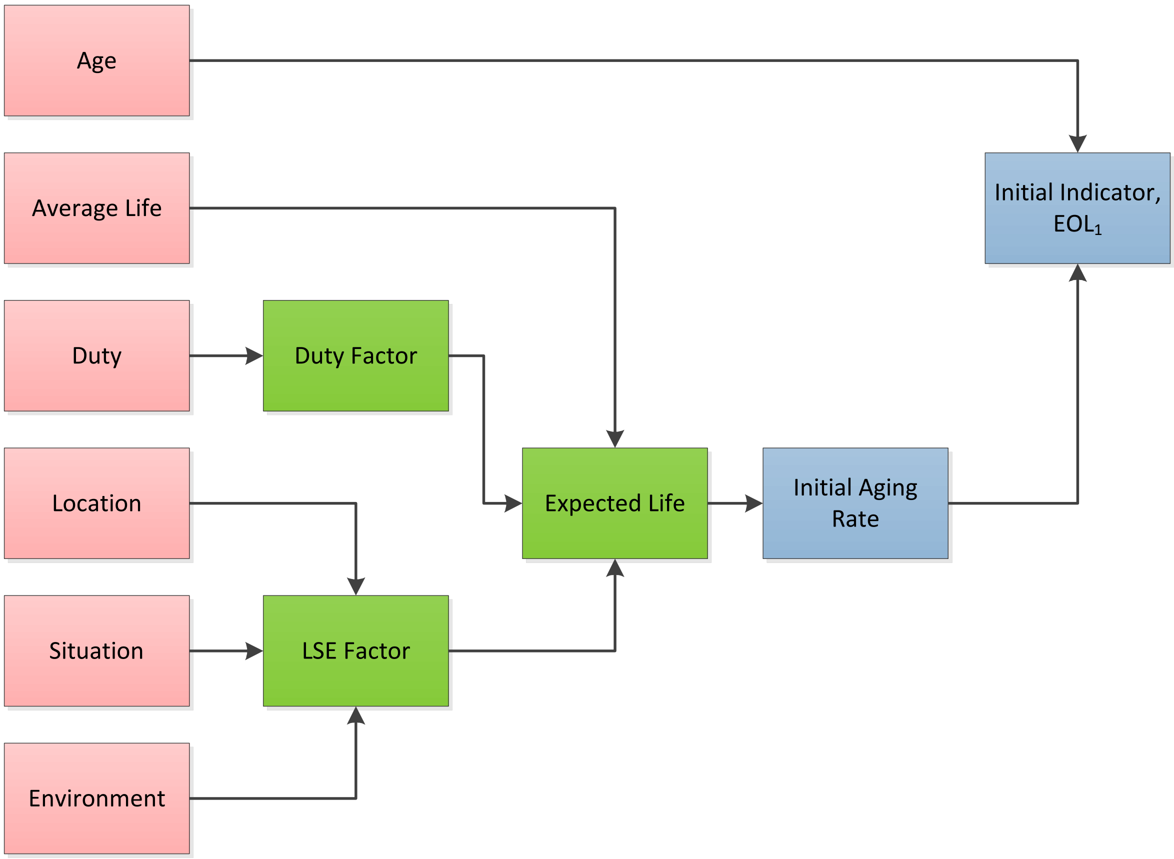

Figure 6.2 - Initial EoL indicator, $EoL_{(1)}$

It should be noted that the derivation of all factors are TO Specific and subject to testing and validation during the implementation of the methodology within the individual TOs.

6.4.2. THE AGEING MECHANISM

The model contains an ageing mechanism, which attempts to estimate the likely future EoL indices for each asset, referred to as EoL_{yn}, which is used to project the future PoF of each asset being considered. The rate of change of the EoL Indicator is non-linear. The degradation processes involved (e.g., corrosion) are accelerated by the products of the process, hence the rate of deterioration increases as the processes proceed.

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

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

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

Nevertheless, most network owners have many years of experience of asset operation and so it is this experience and historical data that is used primarily to determine this relationship. Through the electricity industry's Strategic Technology Programme, it was observed that electrical asset failure rates correlated with asset health according to a semi-Markov relationship[9], leading to an exponential function that for a given asset, can be written as follows:

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

Equation 6

where:

EoL_{t2}	=	EoL Indicator at time t_2
$\mathrm{EoL_{t1}}$	=	EoL Indicator at time t_1
B	=	Ageing rate (see Section 5.4 for details)
$(\mathrm{t_2} - \mathrm{t_1})$	=	Time taken for the asset to move from $\mathrm{EoL_{t1}}$ to $\mathrm{EoL_{t2}}$

The Initial Indicator of each asset is derived using its Initial Ageing Rate (Section 5.4.1 for further details) and its current age (this corresponds to the time taken for the asset to move from the Indicator of a new asset to its Initial Indicator) by the making the following substitutions into Equation 2:

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

Equation 7

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

where:

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

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

$\beta_{1,\mathrm{i}}$ = Initial Ageing Rate of asset i (see Section 5.4.1)

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

cating significant degradation[10].

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

We determine the EoL indicator in future years using the following equation:

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

Equation 8

where ΔT = time between years 0 and n.

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

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

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

[10] This only applies in year 0; EoL can be achieved in future years when there is no condition information.

6.4.3. DERIVATION OF THE INTERMEDIATE EOL INDICATOR, EOL_2,

The second calculation stage, i.e. to find EoL_2, introduces more specific asset information pertaining to observed condition, inspection surveys, maintenance test results and operators experience of each asset. Some typical modifiers, including EoL_1 from the previous stage, are shown in Figure 6.3 below.

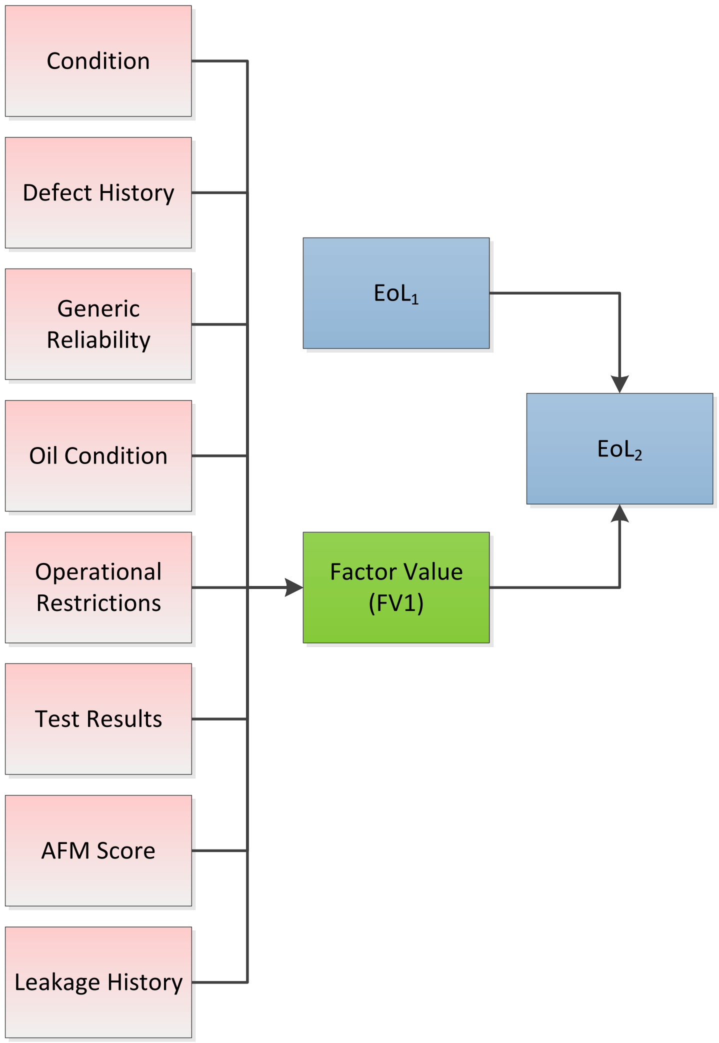

Figure 6.3- Intermediate EoL indicator EoL_2

Modifiers specific to each asset type are identified in asset specific sections of this Section.

6.5. FORECASTING PROBABILITY OF FAILURE

The information above can also be used to determine an approximate rate of deterioration and, therefore, to estimate future asset EoL indices, which can be seen in Figure 6.4 below.

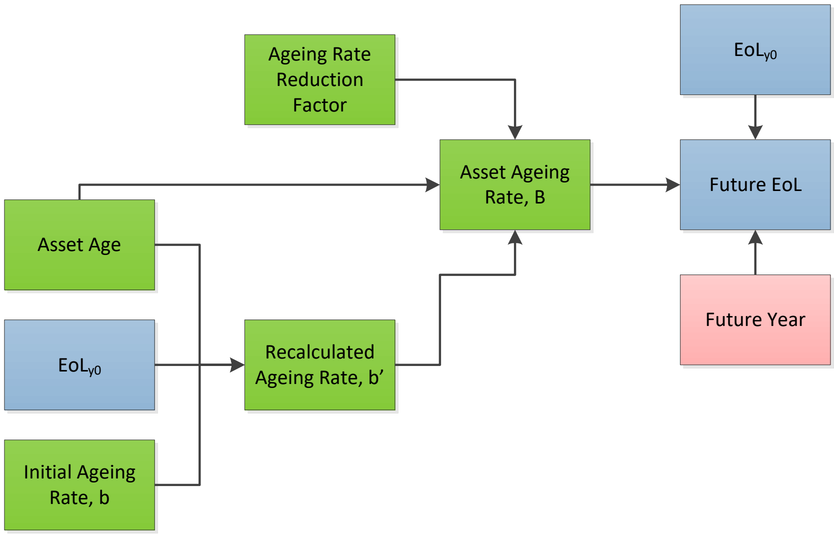

Figure 6.4 - Forecasting Probability of Failure

The current EoL Indicator profile of a group of assets provides a 'snapshot' of the current condition of those assets. It is also possible through the application of Equation 6 to predict how these assets will behave in the future; i.e. how the EoL Indicator will change going forwards. In order to do so, it is first necessary to determine the Final Ageing Rate and the Ageing Reduction Factor for the asset. Once these are known, Equation 9 is used to calculate the EoL Indicator for any asset in any future year t_{YN}, as follows:

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

Equation 9

where:

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

$B_{\mathrm{final,i}}$ = Final Ageing Rate of asset i (see Section 0for details)

$F_{\mathrm{age,i}}$ = Ageing Reduction Factor for asset i (see Section 6.5.2 for details)

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

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

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

6.5.1. FINAL AGEING RATE

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

These assets are identified as those with a Current Health Index below a defined threshold or those younger than a defined age limit.

Thus, when $\mathrm{Age_i} < \mathrm{Age_{recalc}}$ or $\mathrm{EoL_{Y0,i}} \leq \mathrm{EoL_{recalc}}$:

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

Equation 10

where:

$\mathrm{Age_i}$ = Current age of asset i

$\mathrm{Age_{recalc}}$ = Age limit for recalculating the ageing rate

$\mathrm{EoL_{recalc}}$ = Maximum EoL Indicator for using the Initial Ageing Rate

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

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

Equation 11

where:

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

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

6.5.2. AGEING REDUCTION FACTOR

The Ageing Reduction Factor accounts for the increased life expectancy of an asset as it grows older; i.e. it slows the ageing process for assets that have started to age. This is necessary to model the effect of scheduling increasingly intensive or frequent maintenance as an asset approaches the end of its life. The relationship between EoL Indicator and the Ageing Reduction Factor is shown in Figure 6.5.

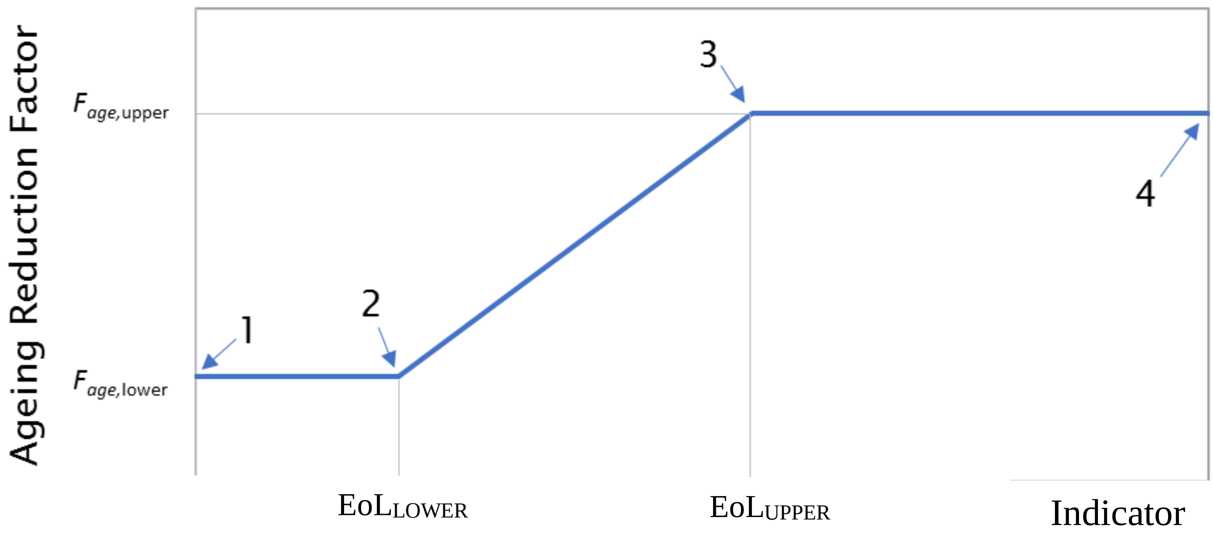

Figure 6.5 - Ageing Reduction Factor Lookup

where:

$\mathrm{F}_{\mathrm{age,lower}}$	=	Lower threshold for the Ageing Reduction Factor
$\mathrm{F}_{\mathrm{age,upper}}$	=	Upper threshold for the Ageing Reduction Factor
EoL_{lower}	=	Value of Indicator below which the lower threshold for the Ageing Reduction Factor is used
$\mathrm{EoL}_{\mathrm{upper}}$	=	Value of Indicator above which the upper threshold for the Ageing Reduction Factor is used

If the EoL Indicator of the asset is between $\mathrm{EoL}_{\mathrm{lower}}$ and $\mathrm{EoL}_{\mathrm{upper}}$, the Ageing Reduction Factor varies linearly as described by Equation 12.

$$\mathrm{F}_{\mathrm{age}} = \mathrm{F}_{\mathrm{age,lower}} + \left(\frac{\mathrm{EoL}_{\mathrm{Y0}} - \mathrm{EoL}_{\mathrm{lower}}}{\mathrm{EoL}_{\mathrm{upper}} - \mathrm{EoL}_{\mathrm{lower}}}\right).\left(\mathrm{F}_{\mathrm{age,upper}} - \mathrm{F}_{\mathrm{age,lower}}\right)$$

Equation 12

The relationship between EoL Indicator and Ageing Reduction Factor is set via a calibration table which defines points 1 to 4 shown in Figure 6.5. The values used to define the Ageing Reduction Factor in all of the models were determined empirically from historical records and are shown in Table 6.1.

Point (See Figure 6.5)	EoL Indicator	Ageing Reduction Factor
1	0.5	1.0
2	2.0	1.0
3	5.5	1.5
4	15.0	1.5

Table 6.1- Ageing Reduction Factor Calibration Values

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

As highlighted previously, the value of c fixes the relative values of the probability of failure for different health indices (i.e. the slope of the curve) whilst k determines the absolute value; both constants are calibration values which are set for each asset class and for each failure mode. Given the importance of these parameters in estimating the asset PoF, it is essential that these parameters are subject to rigorous testing, calibration and review.

6.6. CIRCUIT BREAKER FACTORS AND EOL CALCULATIONS

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

The process for determining the Circuit Breaker EoL Indicator is shown in Figure 2.4. For each stage in the EoL indicator derivation, the overview will identify and name all of the component parts of each derivation and provide a high level explanation of what the component parts represent. Specific factor values can be found in the Company Specific Appendices.

6.6.1. FACTORS WHICH MAY INFLUENCE PROBABILITY OF FAILURE

The following is a list of factors which may influence the Probability of Failure:

- Duty (F_{DY})
- Oil Condition
- SF_6 Condition
- SF_6 Leakage

The EoL_2 module combines the overall condition factor, defect history factor, generic reliability factor, overall SOP factor, overall test result factor, SF_6 condition factor and the SF_6 leakage history factor in order to determine modifying factor ‘FV1’. This is then multiplied with EoL1 from the previous calculation stage to determine EoL_2.

6.7. TRANSFORMER AND REACTOR FACTORS AND EOL CALCULATION

Transformers are assigned an Asset EoL indicator (EoL) according to their known condition and the service history of other similar transformers

The EoL of the overall transformer population is monitored to ensure that replacement/refurbishment volumes are sufficient to maintain sustainable levels of reliability performance, to manage site operational issues associated with safety risks and to maintain or improve environmental performance in terms of oil leakage. Aspects such as strategic spares holdings and refurbishment capabilities are managed to ensure these sustainable levels of reliability performance are maintained and to maintain or improve safety and environmental performance.

Within this methodology, transmission transformers are considered as 'systems' which are made up of 2 components; a transformer (Tx), and a tapchanger (TC). Each component is considered to be an individual asset, with a clearly defined linkage.

For each component of a transformer system, End of Life Modifiers are generated before an overall system EoL indicator is created.

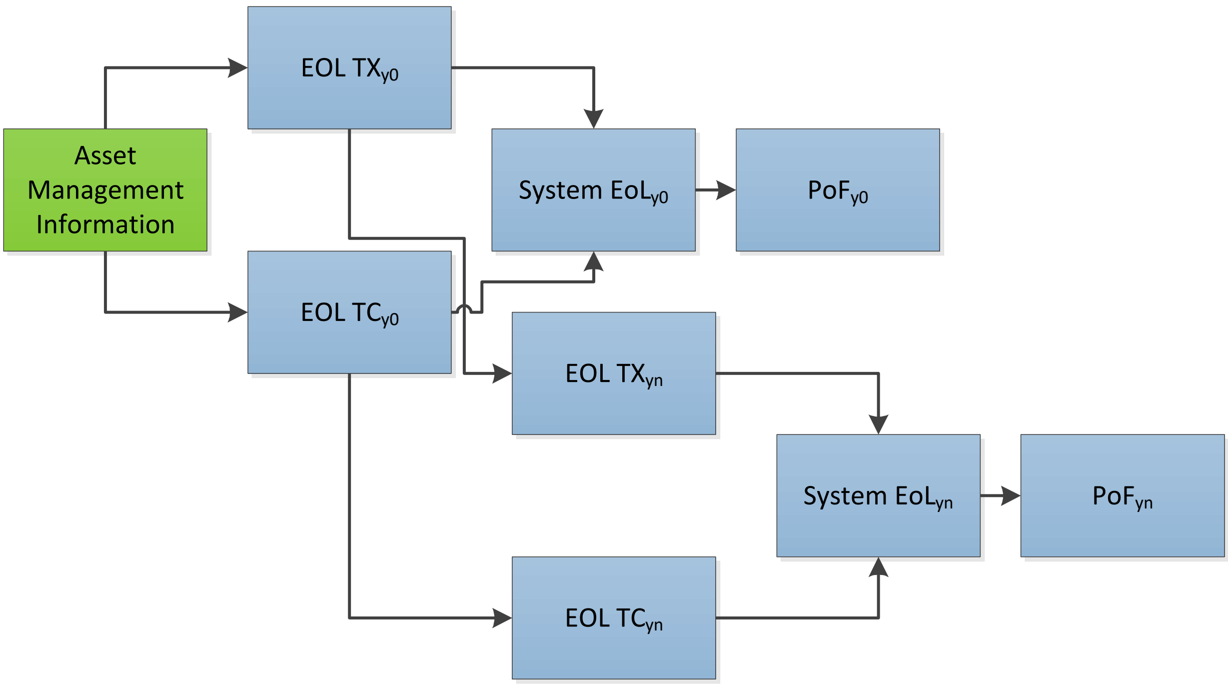

Figure 6.6 - Transformer System Methodology Overview

The Transformer System EoL indicator is defined as follows:

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

Equation 13

Where

$$TxEoL_{(y0)} = max(EoL_{DGA}, EoL_{FFA}, EoL_{MOD})$$

Equation 14

And:

EoL_{DGA} = EoL indicator derived from Dissolved Gas Analysis
EoL_{FFA} = EoL indicator derived from Furfuraldehyde results
EoL_{MOD} = EoL indicator derived from other factors (described below) including the Initial EoL indicator.
This system EoL indicator is then used to calculate a probability of failure, PoF for a number of defined failure modes.

6.7.1. FACTORS WHICH MAY INFLUENCE PROBABILITY OF FAILURE

The following is a list of factors which may influence the Probability of Failure:

- Duty
- Situation Factor
- Oil Condition

The EoL(2) module combines the overall condition factor, defect history factor, family reliability factor, overall test result factor, overall OR factor and the overall oil condition score in order to determine modifying factor 'FV1'. This is then multiplied by EoL_1 to determine EoL_2.

6.7.2. DERIVATION OF TX EOL_{DGA}

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

Each oil sample is analysed for levels of Hydrogen, Acetylene, Ethane, Ethylene, Methane, Oxygen and Nitrogen which provide indications of the internal condition of the transformer. The rate of change of DGA values is also considered so as to take into account each transformer's historical test results. The boundaries for assessment of DGA levels are taken from the Cigre Working Group 15.01 paper, "New guidelines for interpretation of dissolved gas analysis in oil-filled transformers". These boundaries can provide useful information relating to incipient faults within transformers or contamination of the main tank oil from the tapchanger.

EoL_{DGA} is then produced by the following calculation:

$$EoL_{DGA} = \frac{\sum Score(H_{2,} C_2H_{2,} C_2H_{4,} CH_{4,} C_2H_6)}{220}$$

Equation 15

6.7.3. DERIVATION OF TX EOL_{FFA}

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

The average length of the cellulose chains is defined by the degree of polymerisation (DP) which is a measure of the length of chains making up the paper fibres. In a new transformer the DP value is approximately 1000. When this is reduced to approximately 250 the paper has very little remaining strength and is at risk of failure during operation. There is an approximate relationship between the value of furfuraldehyde in the oil and the DP of the paper, which has been established experimentally by the industry. This estimated DP figure is then used to calculate EoL_{FFA}.

Failures involving multi-component systems such as the transformer system under consideration may be regarded as completely interdependent, and therefore links in a 'system chain'. This is the underlying principle behind the derivation of the final present day transformer system EoL indicator EoL_{y0}, which is generated from the larger of the transformer EoL_{y0} and its associated tapchanger EoL_{y0}.

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

Equation 16

6.8. CABLE FACTORS AND EOL CALCULATION

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

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

For each component of cable circuit asset management information is fed into the model in order to produce a component EoL indicator, referred to as EoL_{y0}, before an overall system EoL indicator is created. This system EoL indicator is then used to calculate a probability of failure, PoF for a number of defined failure modes.

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

- Oil
- Non-pressurised
- Submarine cable

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

The models contain an ageing mechanism, which attempts to estimate the likely future EoL indices for each cable to as EoL_{yn}. These future EoL estimations are combined in an identical fashion to the present day EoL calculation, so as to derive an overall cable future EoL, and it is this which is used to project future PoF of each of the cables being considered.

6.8.1. FACTORS WHICH MAY INFLUENCE PROBABILITY OF FAILURE

The following is a list of factors which may influence the Probability of Failure:

- Duty
- Location, Situation and Environment (LSE)

For each cable the LSE factor is calculated from a situation factor and an installation factor, as shown in Figure 6.7 below.

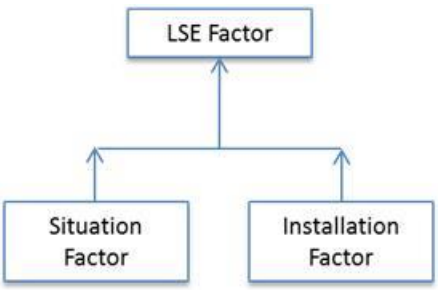

Figure 6.7 - LSE factor

For submarine cables the LSE is determined using the following variables:

- Cable route topology
- Cable situation factor
- Wind/wave factor
- Combined wave and current energy factor

The combination of these variables determines an overall LSE factor (F_{LSE}) using the following equation:

$$F_{LSE} = max(F_T, F_S, F_W, F_E)$$

Equation 17

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

$$L_E = L_A \times (F_{LSE} \times F_{DY})$$

Equation 18

Leak History

The leak history information for a particular circuit is used to determine a leak history factor and an associated minimum EoL for each circuit. The leak history is derived from information on the volume of top-ups over a ten year period.

Fault rate

The fault rate information for a circuit will be used to determine a Fault rate factor and derive a minimum EoL, as shown below.

The EoL_2 module combines the defect history factor, generic reliability factor, overall test result factor, leak history factor and the fault rate factor in order to determine modifying factor 'FV1'. This is then multiplied by EoL_1 to determine EoL_2.

6.9. OVERHEAD LINE FACTORS AND EOL CALCULATION

OHL assets are assigned an Asset EoL indicator (EoL) according to their known condition, the known condition of associated components and the service history of other similar conductors, fittings and towers.

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

- Conductors
- Fittings
- Towers

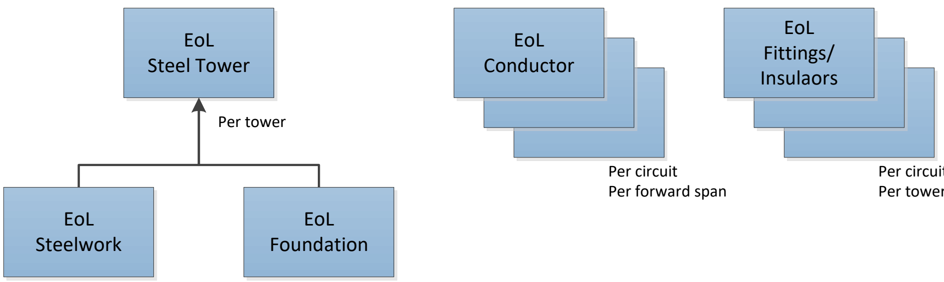

Figure 6.8 - OHL System Overview

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

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

6.9.1. CONDUCTORS

Conductors, as linear assets are referenced as spans of varying length.

For each span of an OHL circuit, asset management information is fed into the model in order to produce a span EoL indicator, referred to as EoL_{y0}, before an overall system EoL indicator is created. This system EoL indicator is then used to calculate a probability of failure, PoF_{y0} for a number of defined failure modes.

The model contains an ageing mechanism, which attempts to estimate the likely future EoL indices for each of the OHL system subcomponents, referred to as
EoL_{y0}. These future EoL estimations are combined to derive an overall OHL system future EoL, and it is this which is used to project future PoF_{y0} of each of the OHL systems being considered.

6.9.1.1. DERIVATION OF THE CONDUCTOR INITIAL EOL INDICATOR, EOL_1.

The initial EoL indicator is based around the age of an asset in relation to the estimated average expected service life which could be reasonably anticipated. This calculation stage does not take into account any condition, defect, inspection or testing information, and simply provides an impression of the likely EoL of an asset given its age, where it is located and its approximate duty. The inputs to the first stage of calculation are shown in Section 6.9.1.2 below.

6.9.1.2. FACTORS WHICH MAY INFLUENCE PROBABILITY OF FAILURE

Location, Situation and Environment (LSE)

For each asset the LSE factor is calculated from the following variables.

- Distance from the Coast
- Altitude
- Corrosion rating e.g. based on proximity to Industrial Pollution

The combination of these three variables determines an overall LSE factor (FL) using the following equation:

$$\mathrm{F_L} = \max(\mathrm{F_D}, \mathrm{F_A}, \mathrm{F_C})$$

Environment

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

The overall LSE factor is derived using the following equation:

LSE Factor = {(Location Factor – Min. Possible Location Factor) x Situation Factor)

+ Min Possible Location Factor} x Environment Factor

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

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

6.9.1.3. DERIVATION OF THE CONDUCTOR INTERMEDIATE EOL INDICATOR, EOL$_2$,

The second calculation stage, i.e. to find EoL$_2$, introduces more specific asset information pertaining to observed condition, test results and operators' experience of each asset. The typical inputs, including EoL1 from the previous stage, are shown in Figure 6.9 - Intermediate EoL indicator EoL.

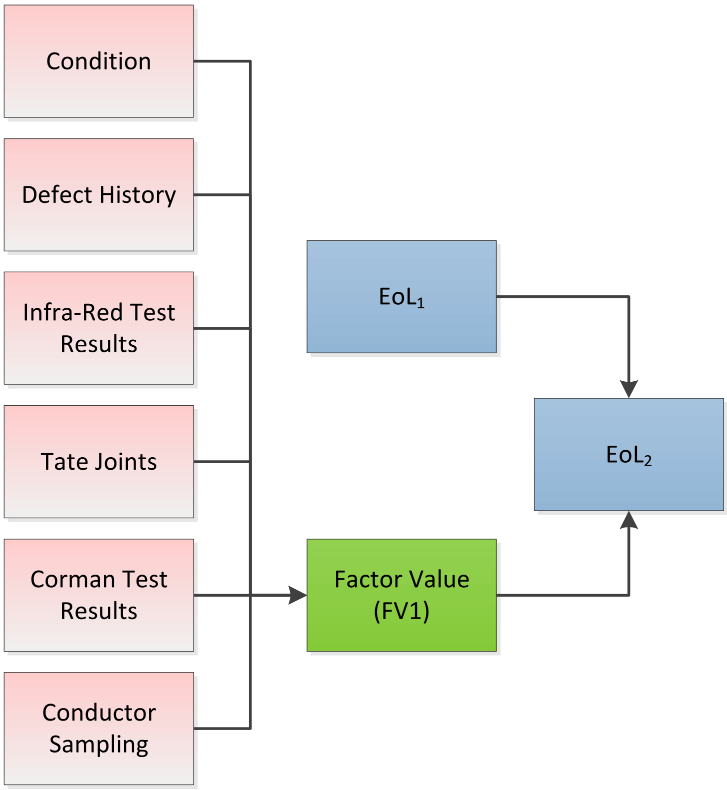

Figure 6.9 - Intermediate EoL indicator EoL$_2$

Condition

The condition of the various components of an asset provide a measure of the degradation processes which may be occurring, and therefore the EoL of the asset. The helicopter assessment of steel tower overhead lines includes a visual assessment of the conductor span.

Defect History

The number of defects experienced on the span over the previous 5 years (including those that have been repaired are identified. Each defect will then be assigned a severity rating (using a scale of 1 to 4, where 4 is the most severe) via a calibration table.

Infra-red Test Results

Helicopter inspections of the Over Head Lines are used to identify hot joints on conductors. This information will be used to derive an infra-red test factor and a minimum EoL value via calibration tables as shown below.

Where tests have been undertaken, the results (either pass, suspect or fail) for each test type are used to derive individual test factors (and if desired minimum EoL indices) and are then combined in order to produce an overall test factor. The overall test factor is included in the formation of modifying factor FV1, while any defined minimum EoL indices are set aside for use later in the process.

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

The test results are used to derive a Cormon EoL indicator via a calibration table of the form shown below. The tests are conducted on a span or number of spans and the results are then applied to the whole circuit. The test results are converted to a score, e.g. 1-4.

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

The test results are used to derive a Conductor Sampling EoL indicator via a calibration table of the form shown below. The tests results are conducted on a span or number of spans and then applied to the whole circuit. The test results are converted to a score, e.g. 1-5.

6.9.1.4. DERIVATION OF THE CONDUCTOR FINAL EOL INDICATOR, EOLY0

The final stage of the conductor present day EoL indicator, EoL_{Y0}, compares each individual factors intermediate EoL indicator as shown below:

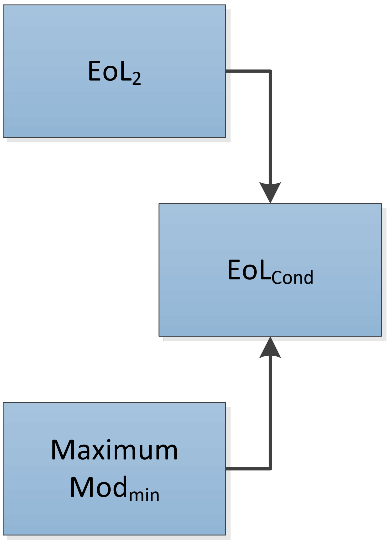

Figure 6.10 - Conductor Final EoL indicator, EoL_{Cond}

6.9.2. FITTINGS

To attach, insulate and join conductor spans various fittings and insulators are used. Over the course of the lifetime of these assets an EoL indicator needs to be calculated (on a per circuit and a per tower basis) as summarised in the schematic diagram below.

6.9.2.1. DERIVATION OF THE FITTINGS INITIAL EOL INDICATOR, EOL_C.

The initial EoL indicator is based around the age of an asset in relation to the estimated average expected service life which could be reasonably anticipated. This calculation stage does not take into account any condition, defect, inspection or testing information, and simply provides an impression of the likely EoL of an asset given its age, where it is located and its approximate work load. The inputs to the first stage of calculation are shown in Section below.

6.9.2.2. FACTORS WHICH MAY INFLUENCE PROBABILITY OF FAILURE

Location, Situation and Environment (LSE)

For each asset the LSE factor is calculated from the following variables.

- Distance from the Coast
- Altitude
- Corrosion rating e.g. based on proximity to Industrial Pollution

The combination of these two variables determines an overall LSE factor (FLSE) using the following equation:

The overall LSE factor is derived using the following equation:

LSE Factor = ((Location Factor – Min. Possible Location Factor) x Situation Factor) + Min Possible Location Factor) x Environment Factor

Starting with the average life (LA) for that asset class, the Duty and LSE factors are used to set an expected life (LE) for each asset.

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

6.9.2.3. DERIVATION OF FITTINGS - FINAL EOL INDICATOR, EOLY0

The second calculation stage, i.e. to find EoL_{Y0}, introduces more specific asset information pertaining to observed condition, test results and operators' experience of each asset. The typical inputs, including EoL_C from the previous stage, are shown in Figure 6.11.

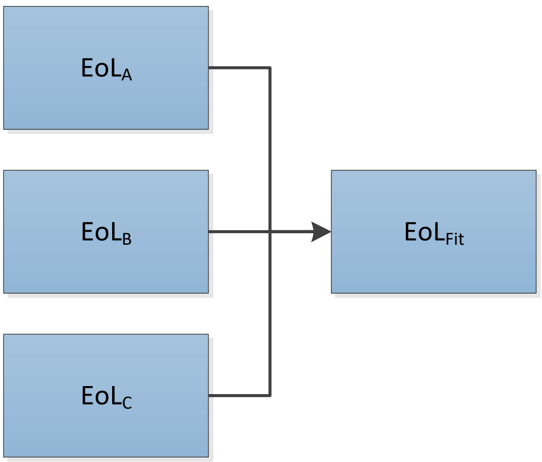

Figure 6.11 - Final EoL indicator

Condition

Where reliable and robust information provides definitive information on asset condition, the information is used to directly derive a condition based EoL indicator. This is depicted in the schematic diagram shown below.

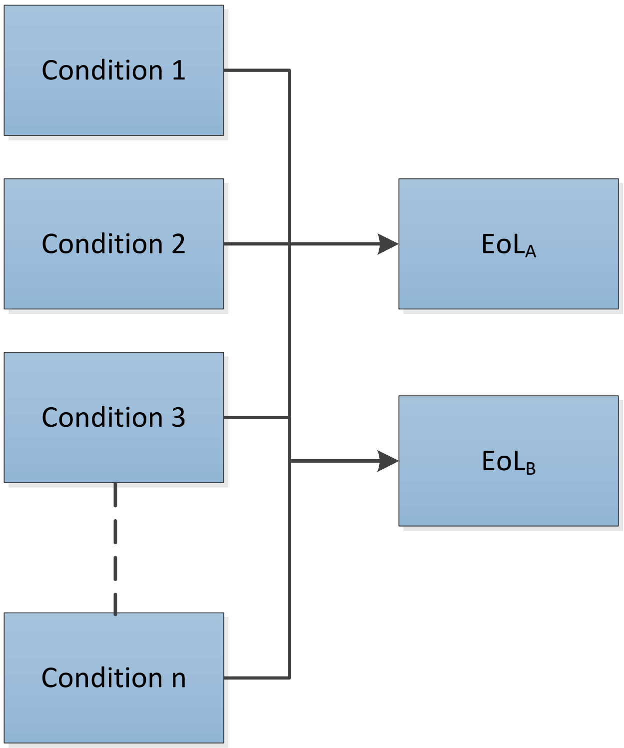

Figure 6.12 - Derivation of condition based EoL Indices for fittings

A number of individual condition points are assessed or rated using a pre-defined scale (typically 1 to 4 or 1 to 5). Each condition rating is then assigned a condition score via a calibration table. Each condition point has its own specific calibration table for defining the condition score.

Condition Score Calibration

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

EoL$_a$ is the highest of the condition scored divided by a calibration value, whilst EOL$_b$ is the sum of the three highest condition scores divided by a second calibration value. Where condition scores are not provided, a default condition score is applied.

6.9.3. TOWERS

The steel tower EoL indicator is formed from a combination of a steelwork EoL and a tower foundation EoL indices.

The Tower EoL indicator is defined as follows:

$$EoL_{(T)} = weighted\ average\left(Tower\ Steelwork\ EoL_{y0}, Tower\ Foundations\ EoL_{y0}\right)$$

6.9.4. STEELWORK EOL INDICATOR

6.9.4.1. DERIVATION OF STEELWORK EOL$_A$ AND EOL$_B$

The first stage of the steel work EoL indicator is derived using the observed condition information collated from surveys and inspections, as shown below.

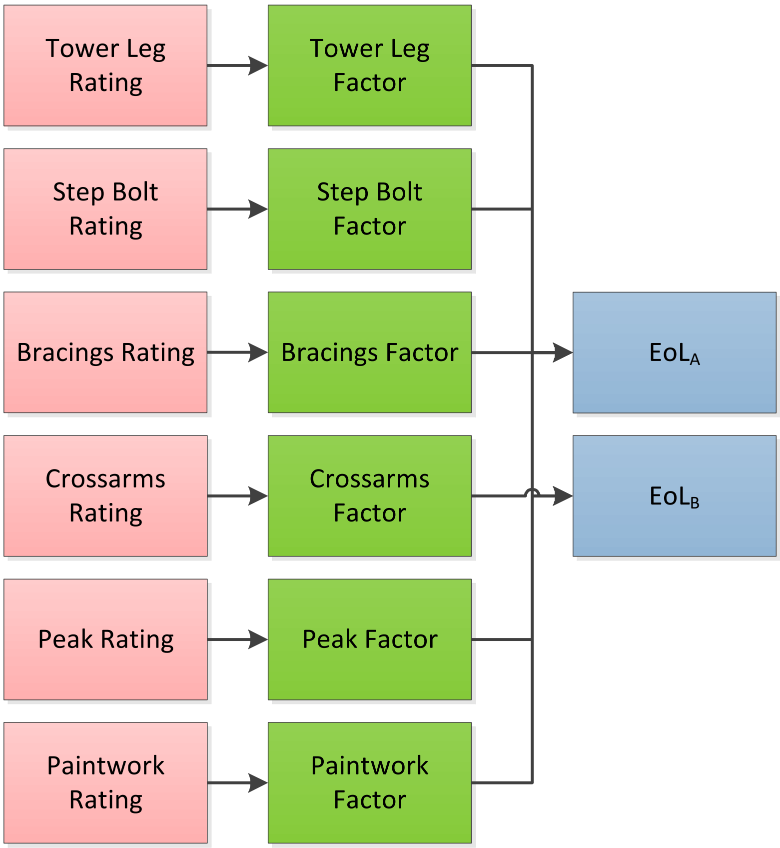

Figure 6.13 - Derivation of initial steelwork indicators

Observed condition scores taken from inspection or condition assessments and the year in which the condition assessments took place are entered into the model. Each condition point is assigned a condition score via a series of calibration lookup tables. Condition points include scores for the tower legs, step bolts, bracings, crossarms, peak, paintwork.

EoL$_A$ is derived from the worst of the condition points found, while EoL$_B$ is derived using the sum of the condition points scores divided by a calibration 'divider'. This creates two EoL indices which represent the condition of the tower steelwork in the year of condition assessment; the Implementation will then age these EoL indices to the present year.

6.9.4.2. DERIVATION OF STEELWORK EOL INDICATOR EOL$_C$

An 'age based' EoL indicator, EoL$_C$, is derived from the asset age, last painting date and the expected service life of the tower as shown in Figure 6.14 below. This is only used

i. if no inspection data is available to derive EoL$_A$ and EoL$_B$, or
ii. to provide boundaries for the HIs derived from inspection data.

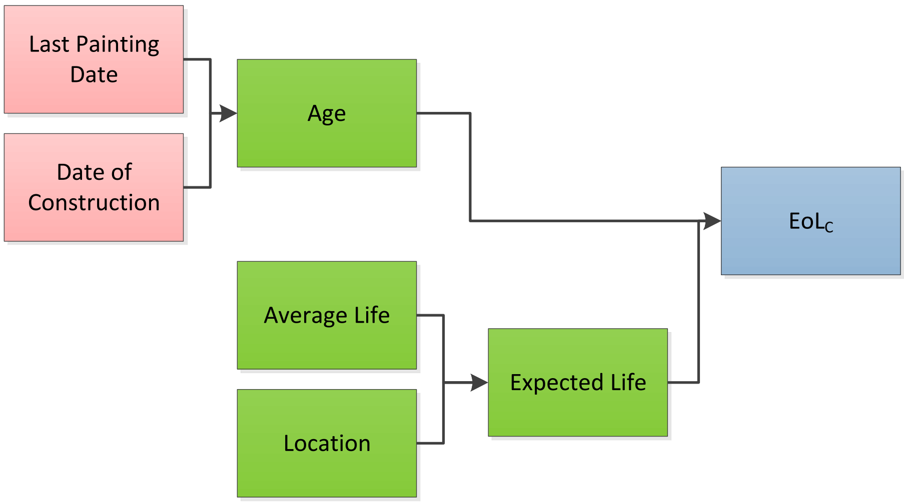

Figure 6.14 - Steelwork EoL indicator EoL(c)

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

6.9.4.3. DERIVATION OF STEELWORK EOL$_S$

The final tower steelwork EoL indicator, EoL$_S$, which represents the present day overall condition of the tower steelwork is determined from EoL$_A$, EoL$_B$ and EoL$_C$ as depicted below.

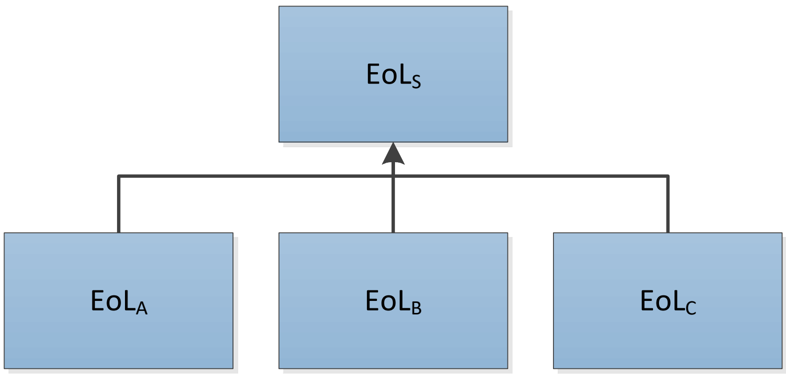

Figure 6.15 - Tower Steelwork EoL$_S$

Where detailed condition assessment information is not available, the model will not be able to calculate EoL$_A$ or EoL$_B$, and therefore EoL$_S$ will equal EoL$_C$.

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

6.9.5. FOUNDATION EOL INDICATOR

6.9.5.1. DERIVATION OF THE FOUNDATION EOL INDICATOR

The Implementation calculates an EoL indicator for each set of tower foundations for each tower position. The model uses information relating to the type of foundation, the environment in which the foundation is situated, along with more specific foundation test results and inspection information. The first stage of EoL indicator calculation determines the foundation initial EoL indicator, which is shown in below.

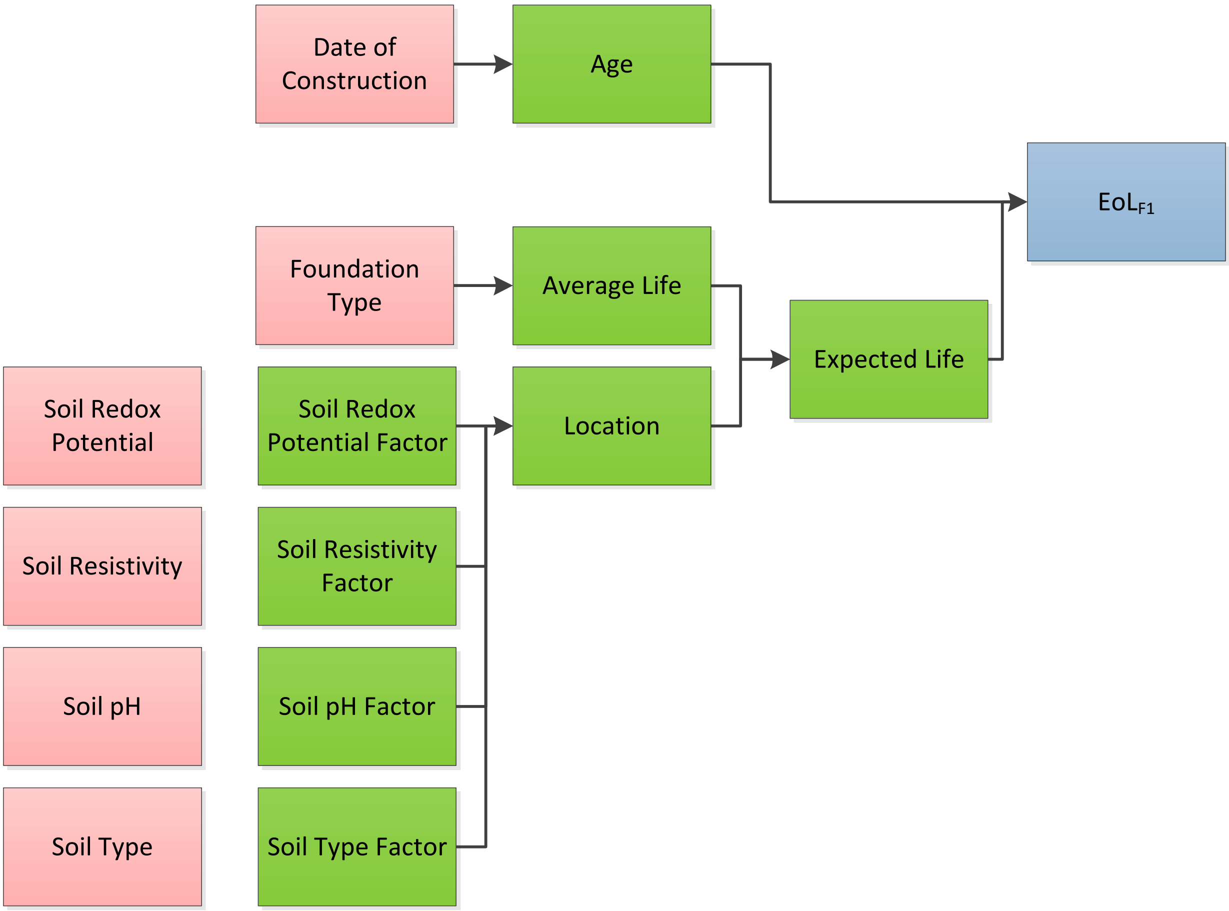

Figure 6.16 - Initial Foundation EoL indicator, EoL_{F1}

The overall location factor for foundations is either derived from the specific soil test results indicated in Figure 6 or from an overall soil type factor. If neither are available the factor defaults to a neutral value of 1.

6.9.5.2. FOUNDATION INTERIM EOL INDICATOR

The second calculation stage, i.e. to find EoL_2, introduces more specific asset information pertaining to observed condition, inspection surveys, maintenance test results and operators experience. The inputs, including the Foundation EoL1 from the previous calculation stage, are shown below.

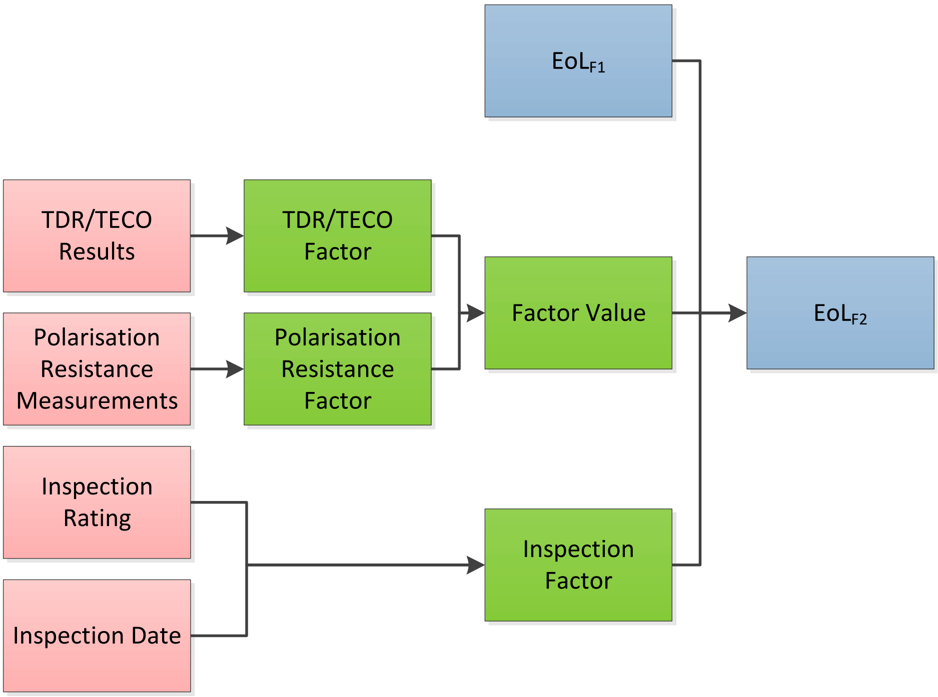

Figure 6.17 - Interim Foundation EoL indicator EoL_{F2}

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

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

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

6.9.6. STEEL TOWER EOL INDICATOR

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

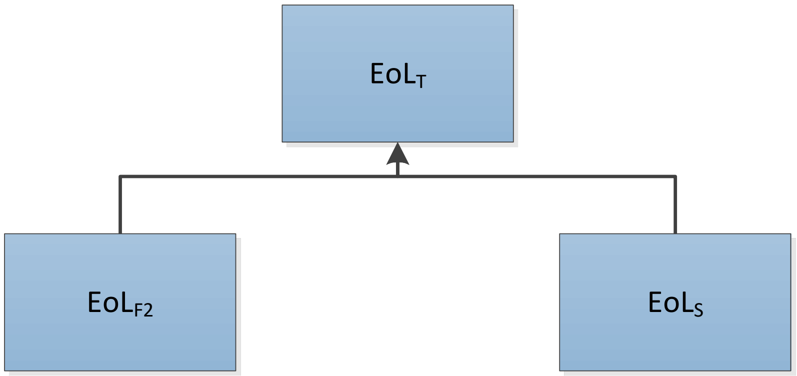

Figure 6.18 - Steel Tower EoL indicator

Once each of the input heath indices have been created, the Steel Tower EoL indicator is formed by taking a weighted average of both the tower steelwork and the foundation EoL indices. This weighted average is subject to a minimum EoL indicator override which is determined by calibration values. Traditionally the weighting applied to the tower steelwork to foundation is in the region of 1:3, however this ratio can be changed as part of a calibration review.

7. REPORT FINDINGS

The analysis described so far is only credible if it is documented, understood and the findings are known to be meaningful. Section 5.4 of EN 60812 provides guidance on the scope and content of FMEA reporting, which should include a detailed record of the analysis used and a summary of the failure effect identified.

The implementation by SP Transmission/SHE Transmission uses a managed computing tool to provide clear, auditable documentation of the precise calculation steps used in the analysis.

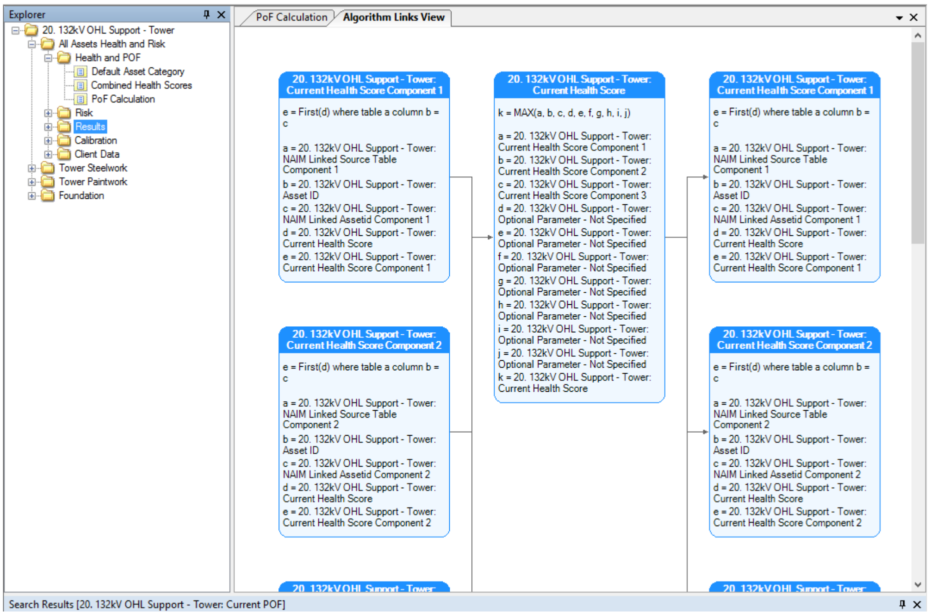

Figure 7.1 Example algorithm view on SP Transmission/SHE Transmission modelling environment